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Presented by

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Gap Analysis for the Integration of the WEF Nexus Technologies in the Elaboration and Implementation of National Climate Policies (NDC and NAP) in Benin Republic, West Africa

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DECLARATION

I, **Assou Yves KOKOUVI** hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

By my signature below, I am submitting this document in partial fulfilment of the requirements for a degree from Pan African University and declare that I have not submitted this document to any other institution for the award of an academic degree, diploma or certificate.

Assou Yves KOKOUVI **Date** : March 22th, 2024

CERTIFICATION

I, **Dr. Ambe Emmanuel Cheo**, hereby certify that this work was entirely carried out by Assou Yves KOKOUVI, a student in MSc. Climate Change Engineering at the Pan African University, Institute for Water and Energy Sciences, including Climate Change (PAUWES), under my supervision for the purpose of obtaining the Master of Science degree, with the Option: Climate Change Engineering.

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DEDICATION

With pleasure and gratitude, I dedicate this work to:

My father, **Thomas KOKOUVI**, who instilled in me the love of hard work, and whose fervent desire has always been to see me succeed in life. May this humble work bring you satisfaction and fulfill your expectations!

My dear and virtuous mother, **Awawou DJESSOU**, for your countless sacrifices and hardships since my childhood; your motherly spirit has always persevered to ensure that happiness lies only in the success of your children. May this endeavor be the dawn of your dreams. May Almighty God grant you a radiant life!

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ABSTRACT

Climate change poses a serious threat to sustainable development in Africa, particularly in Benin, where agriculture, fisheries, and coastal resources are heavily impacted. The objective of this study was to propose strategies for integrating Water-Energy-Food (WEF) Nexus technologies into Benin's national climate policies. A comprehensive literature review, bibliometric analysis, and assessment of Nexus integration in Benin's NDC and NAP were conducted using the SWITCH-Med framework. The exhaustive bibliometric analysis of scientific publications on the Nexus evaluated knowledge production in Africa and Benin. Additionally, the SWITCH-Med assessment grid was used to thoroughly analyze the degree of Nexus integration in Benin's Nationally Determined Contribution (NDC) and National Adaptation Plan (NAP). The results show that resources in the WEF Nexus sectors are available but their accessibility needs improvement, with a WEF Nexus index increasing from 44.3 points in 2019 to 47.1 in 2023. Gaps were identified in the sectoral management and intersectoral coordination of resources, and scientific production on the Nexus in Africa, including in Benin, remains limited. The NDC and NAP partially and indirectly integrate the Nexus, at 70% for the NAP and 50% for the NDC. Therefore, there is a need to promote integrated and trans-sectoral climate planning in Benin, optimizing resource use and multiple benefits. Specific recommendations are made to strengthen Benin's scientific research on the Nexus, while identifying the need to study the environmental aspect of the Nexus for better sustainable resource management.

Keywords: Water-Energy-Food Nexus Technologies, Bibliometric analysis, Climate Change, Gaps Analysis, Nationally Determined Contribution, National Adaptation Plan

RESUME

Le changement climatique menace gravement le développement durable en Afrique, notamment au Bénin où l'agriculture, la pêche et les ressources côtières sont fortement impactées. L'objectif de cette étude était de proposer des stratégies pour intégrer les technologies de la nexus eau-énergie-alimentation dans les politiques climatiques nationales du Bénin. Une revue de littérature approfondie, une analyse bibliométrique et une évaluation de l'intégration du Nexus dans le NDC et le PAN du Bénin ont été réalisées à l'aide de la grille SWITCH-Med. L'analyse bibliométrique exhaustive des publications scientifiques sur le Nexus a permis d'évaluer la production de connaissances en Afrique et au Bénin. Par ailleurs, la grille d'évaluation SWITCH-Med a été utilisée pour analyser de manière approfondie le degré d'intégration du Nexus dans le Contribution Déterminée au niveau National (CDN) et le Plan d'Adaptation National (PAN) du Bénin. Les résultats montrent que les ressources des secteurs du Nexus WEF sont disponibles mais leur accessibilité doit être améliorée, avec un indice Nexus WEF qui a augmenté de 44,3 points en 2019 à 47,1 en 2023. Des lacunes ont été identifiées dans la gestion sectorielle et la coordination intersectorielle des ressources, et la production scientifique sur le Nexus en Afrique, dont au Bénin, reste limitée. Le NDC et le PAN intègrent partiellement Nexus de façon indirecte, à hauteur de 70% pour le PAN et 50% pour le NDC. Il est donc nécessaire de promouvoir une planification climatique intégrée et trans-sectorielle au Bénin, optimisant l'utilisation des ressources et les bénéfices multiples. Des recommandations spécifiques sont formulées pour renforcer la recherche scientifique béninoise sur le Nexus, tout en identifiant la nécessité d'étudier l'aspect environnemental du Nexus pour une meilleure gestion durable des ressources.

Mots-clés : Technologies du Nexus Eau-Énergie-Alimentation, Analyse bibliométrique, Changement climatique, Analyse des lacunes, Contribution Déterminée au niveau National, Plan National d'Adaptation

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LIST OF ABBREVIATIONS AND ACRONYMS

APV: Agrivoltaic or Agrophotovoltaic

ASAL: Arid and Semi-Arid Lands

ECOWAS: Economic Community of West African States

FAO: Food and Agriculture Organization of the United Nations

GDP: Gross Domestic Product

HDI: Human Development Index

IEA: International Energy Agency

IPCC: Intergovernmental Panel on Climate Change

IRENA: International Renewable Energy Agency

KM : Kilometer

KM^2 : Kilometer Square

M^2 : Squared Meter

M^3: Cubic meter

MM : Milimeter

NAP: National Adaptation Plan

NDC : Nationally Determined Contribution

PV: Photovoltaics

PV-GM: Ground-Mounted Photovoltaics

RCP: Representative Concentration Pathway

SDGs: Sustainable Development Goals

UN: United Nations

UNFCCC: United Nations Framework Convention on Climate Change

UNICEF: United Nations International Children's Emergency Fund

USAID: United States Agency for International Development

WASH: Water, Sanitation and Hygiene

WEF: Water-Energy-Food

1. Introduction

1.1. Background and context of the study

Climate change poses one of the greatest threats to sustainable development worldwide. The impacts of rising global temperatures are already being felt through more frequent and severe natural disasters. According to the IPCC (2022), the number of weather-related disasters has increased fivefold over the past 50 years, costing an average of $200 billion in losses annually. In Africa, climate change risks exacerbate poverty and threaten progress on achieving the UN Sustainable Development Goals (SDGs) due to the continent's high vulnerability and low adaptive capacity (Niang *et al*., 2014).

Africa is experiencing the adverse effects of climate change through shifts in rainfall patterns and rising temperatures. The UN Economic Commission for Africa (UNECA, 2021) reports sub-Saharan Africa has warmed about 1°C over the past century, with 11 of the 12 warmest years on record occurring since 2000. This is disrupting agricultural production, which accounts for 15-30% of GDP and over 60% of jobs across many African nations (World Bank, 2022). According to the Food and Agriculture Organization (FAO, 2022), climate change could reduce crop yields in Africa by up to 50% by 2100 if no action is taken. Water resources are also under threat, exacerbating water scarcity for over 300 million Africans by 2025 (WWF, 2021). The UN World Water Development Report (2022) found North Africa will face the largest increase in water stress globally by 2050 due to climate change, with over 97% of the population living with water scarcity. In coastal nations, rising sea levels and intensifying storms imperil lives and infrastructure. For example, Benin experienced over $400 million in damages from severe flooding in 2019 according to government reports (Government of Benin, 2021). In response to the mounting climate emergency, the Paris Agreement set the goal of limiting global warming to well below 2°C through Nationally Determined Contributions (NDCs) outlining domestic climate actions by each country (UNFCCC, 2015). To date, over 190 parties have ratified the accord (UNFCCC, 2022). However, achieving both the Paris temperature goals and sustainable development targets poses immense challenges, especially for developing nations with limited financial and technical resources to invest in climate solutions. According to the United Nations Environment Programme (UNEP, 2021), Africa requires $3 trillion in investment by 2030 to implement its NDCs and transition to low-carbon, climate-resilient development pathways. One approach gaining recognition to help address these challenges is through integrated management of interconnected natural resources known as the water-energy-food (WEF) nexus. The nexus recognizes the synergies and trade-offs between different sectors like water, energy, agriculture, and the environment to encourage cooperation rather than working in isolation (Endo *et al*., 2017). According to Ringler et al. (2013), this nexus-based approach helps maximize co-benefits and efficiencies while minimizing negative externalities through optimized cross-sectoral planning and governance.

In sub-Saharan Africa, WEF nexus solutions present opportunities to boost resilience, food and energy security. For example, the International Renewable Energy Agency (IRENA, 2019) estimates agricultural waste could provide up to 10% of Africa's total power needs through conversion to biogas and electricity. Multipurpose dams built for hydropower can also support irrigation for an additional 20 million hectares of cropland (FAO, 2014). Integrated landscape management practices likewise protect 30-50% of carbon stored in tropical forests and grasslands, vital carbon sinks and sources of livelihoods (WWF, 2019).

Benin is highly vulnerable to climate change impacts that threaten its key economic sectors of agriculture, fisheries, coastal resources and water supplies. Agriculture alone contributes over 30% of GDP and employs roughly 80% of the labor force (Government of Benin, 2021). Benin's NDCs and National Adaptation Plans (NAPs) prioritize actions for climate adaptation and mitigation across water, energy, food and land use.

This study aims to mainly conduct a gap analysis of the integration of WEF Nexus technologies in the design and implementation of Benin's climate policy documents (NDC and NAP). It will analyze nexus synergies and opportunities, and the gap of taking into account the WEF nexus in the development and implementation of climate plans (NDC and NAP). The results should provide practical and scientific recommendations to guide the implementation of Benin's NDCs and NAPs through a WEF nexus approach.

1.2. Clarification of basic's concepts

The concept of the water-energy-food (WEF) nexus emerged in the late 2000s in response to the need for more integrated resource management across sectors (Bizikova *et al*., 2013). Nexus thinking recognizes that our demand for food, energy, and water are deeply interconnected, and decisions or actions in one sector often impact the others (Endo *et al*., 2017).

Traditionally, these resources had been planned and governed separately in sectoral "silos" without consideration for cross-sectoral linkages and trade-offs (Ringler *et al*., 2013). However, as demand for all three resources rapidly increased due to population and economic growth amidst climate change impacts, the siloed approach proved unsustainable and inefficient. The WEF nexus approach aims to overcome this by promoting coordination and joint planning across water, energy, food, land and other linked systems (FAO, 2014). There are three primary components that define the WEF nexus (ICWE, 2021). The first is the physical nexus, which describes the biophysical interconnections and natural flows between water, energy and food resources. For example, large amounts of water are required to produce energy through thermoelectric power plants that use water for cooling, while irrigation is essential for growing food but also a major consumer of freshwater (Kartheikeyan *et al*., 2020).

The second component is the socio-economic nexus, which involves the social, institutional and economic interdependencies between sectors. This includes factors like virtual water trade through international food markets, rural electrification programs relying on agricultural residues for biomass energy, and impacts of energy prices on irrigation pumping costs for farmers (WWAP, 2018).

The third component is the policy and legislative nexus, referring to the policy coherence and governance challenges across sectors due to differing institutional mandates and planning horizons of ministries or agencies overseeing water, energy, agriculture and the environment (Bizikova et al., 2013). Integrated WEF nexus thinking and planning aims to overcome these governance silos by bringing various stakeholders together.

Overall, the nexus approach views water, energy and food security as inextricably linked and promotes synergetic solutions that optimize co-benefits across sectors through coordinated systems analysis, planning and management (Hoff, 2011). This helps boost resource use efficiencies, minimize conflicts and trade-offs, and strengthen climate resilience compared to addressing each sector separately (Endo *et al*., 2017).

1.3. Problem statement and motivation for the study

While Benin has made progress in developing climate plans through its NDCs and NAPs, implementing priority actions faces numerous challenges due to financial, technical and capacity limitations. According to the latest biennial update report submitted by Benin to the UNFCCC (Government of Benin, 2021), a lack of investment remains one of the major barriers to climate action. The country requires an estimated $4.8 billion annually through 2030 for climate adaptation alone, far exceeding its national budget. At the same time, traditional sectoral approaches fail to maximize opportunities for synergies between climate actions. Projects are often planned in isolation without considering cross-sectoral co-benefits (Bizikova *et al*., 2013). This can result in duplication of efforts or even increased trade-offs. For example, expanding irrigation without regard for return flows can over-abstract water needed for hydropower generation downstream (Ringler *et al*., 2013). Mainstreaming the water-energy-food nexus offers a promising alternative framework to help Benin overcome these challenges. By promoting joint planning and governance across sectors, the nexus approach can boost resource use efficiencies to “do more with less” (FAO, 2014). This multi-benefit characteristic of nexus solutions makes them well-suited to attract climate financing from various funding streams (IRENA, 2019). For instance, a single irrigation-hydropower project may tap funds earmarked for both agriculture adaptation and renewable energy projects.

Given Benin's vulnerability to climate impacts on water, food and energy security, nexus solutions also strengthen the country's resilience to climate risks. Agricultural waste-to-energy provides a diversified energy source less vulnerable to droughts affecting hydropower (Karthikeyan et al., 2020). Multipurpose "green" infrastructure like nature-based flood defenses and managed aquifer recharge boost multiple sectors simultaneously (WWF, 2021).

This study aims to demonstrate how a science-based assessment of nexus opportunities can help Benin maximize synergies between climate actions, attract increased climate financing, and build adaptive capacity. The results are expected to provide practical recommendations for operationalizing nexus thinking to support NDCs and NAPs implementation across vulnerable nations like Benin.

1.4. Research objectives, questions and Hypothesis

1.4.1. Research Objectives

- **Main Objective**

This study aims to mainly conduct a gaps analysis of the integration of WEF Nexus technologies in the design and implementation of Benin's climate policy documents (NDC and NAP).

- **Specific Objectives**

To effectively achieve the main objective of this work, it was divided into three specific objectives. These were :

- Assess the nature and extent of the interconnection and interdependence of water, energy, and food (WEF) sector resources in Benin, with a focus on the availability and accessibility of these resources
- Assess existing gaps in the integration of the Nexus WEF technologies in Benin's climate policy documents, notably the Nationally Determined Contributions (NDCs) and the National Adaptation Plan of Action (NAP)
- Propose specific and adapted recommendations to fill the gaps identified in the consideration of the WEF Nexus in the design of Benin's climate policies.

1.4.2. Research Questions

- How can the physical, socio-economic and policy interlinkages between water, energy and food sectors in Benin be characterized based on a review of literature and stakeholder perspectives?
- What gaps exist in considering cross-sectoral synergies, trade-offs and nexus-based solutions when analyzing how Benin's NDCs and NAP address priority climate actions?
- What specific recommendations can be made to strengthen integration of the nexus concept in the design and implementation of Benin's climate policies based on opportunities identified?

1.4.3. Research Hypothesis

- Strong interdependencies exist between key sectors like irrigation, hydropower, agriculture and fisheries that demonstrate the relevance of a nexus approach in Benin's national context.
- The policy documents do not fully recognize nexus opportunities and a review will find room for more integrated planning across water, energy and food sectors.
- Mainstreaming nexus thinking in national strategies through optimized resource use, multi-benefit projects and cross-sectoral coordination will enhance climate action in Benin Republic

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1.5. Scope of the Study

This study will focus on the integration of the water-energy-food nexus approach in Benin's climate policy documents, specifically the Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs). A gap analysis will be conducted to assess the level of consideration given to cross-sectoral linkages and opportunities for synergistic solutions between water, energy and food sectors. A review of academic literature and relevant policy and planning documents will characterize the key physical, socio-economic and policy interdependencies in Benin's national context. The analysis will then evaluate how Benin's latest NDCs and NAPs submission address priority climate actions from an integrated resource management lens. Based on gaps identified, recommendations will be developed for mainstreaming nexus thinking to strengthen climate action implementation. This includes proposals for optimized resource planning, identification of pilot nexus projects aligned with NDCs/NAPs, and enabling frameworks for cross-sectoral coordination and blended climate financing of integrated solutions. The scope is focused on Benin as a case study for applying nexus principles in national climate policy processes.

1.6. Significance and relevance of the study

The proposed study on the potential of WEF Nexus Technologies for implementing NDCs and NAPs in Africa, with a focus on Benin's Republic, is highly relevant in the current context of climate change and sustainable development. The WEF Nexus represents an interconnected system where the management of water, energy, and food resources is inherently linked, necessitating an integrated approach to address the complex interdependencies of these resources. This study aims to deepen our understanding of the WEF Nexus paradigm within the context of NDCs and NAPs, building on existing literature and conducting a bibliometric analysis to comprehensively map the scholarly landscape on this intersection. By analyzing case studies and examples from Benin's Republic, this study will provide insights into the potential of WEF Nexus Technologies for promoting sustainable development and achieving climate goals in Africa. The findings of this study will be of great value to policymakers, researchers, and practitioners working in the fields of climate change, sustainable development, and natural resource management.

2. LITERATURE REVIEW

2.1. Conceptualizing the Water-Energy-Food Nexus

2.1.1 Definitions and origins of the nexus concept

The concept of nexus refers to the interdependencies and competition that exists between natural resources. It emerged in the 2010s with the objective of better taking into account these interrelationships in resources management and public policy planning.

Several definitions of the nexus have been proposed. Leck *et al*. (2015) defined it as "an analytical approach that recognizes the interlinkages between water, energy, and food". Mohtar and Rosen (2015) also emphasized these three key elements while including environmental, social and economic dimensions. Endo *et al*. (2017) proposed a broader definition encompassing all interacting resource systems such as water, energy, land, ecosystems and climate.

The nexus concept initially emerged in the 2010s driven by international organizations such as the Water Resources Institute, the World Economic Forum and the Bonn2011 Nexus Conference (Mohtar and Rosen, 2015; Leck *et al*., 2015). The idea was to promote an integrated and systemic management of these interdependent resources, often treated in a sectoral manner by public policies (Endo *et al*., 2017). The nexus aimed to improve the efficiency and resilience of systems facing risks such as climate change, population growth or urbanization (Kumazawa *et al*., 2017).

This concept has since been widely used in scientific literature and sustainable development strategies carried by international organizations. It is now recognized as a useful decision-making tool for systematically addressing environmental, economic and social issues interlinkages. For example, over 500 research articles mentioning the "water-energy-food nexus" were published between 2010-2020 according to Web of Science.

Figure 1: The Anthropocentric Water-Energy-Food Nexus Framework (Simpson *et al*., 2020)

2.1.2. Physical, socio-economic and policy dimensions

The nexus involves various physical, socio-economic and policy dimensions due to the multi-sectoral nature of resources interlinkages.

Physically, water is needed for food production, accounting for over 80% of water withdrawals globally according to FAO data (Terrapon-Pfaff *et al.*, 2018). Agriculture is the largest consumer of freshwater resources. In turn, food production relies on water for irrigation but also requires significant energy inputs for agricultural machinery, transport, processing and packaging (Leck et *al.*, 2015). At the global level, 19% of total water withdrawals are associated with thermoelectric cooling, making the energy sector another large water user (Sesma-Martín and Puente-Ajovín, 2022). Energy production also depends on water availability, especially for hydroelectricity and thermal power plants using water for cooling (Terrapon-Pfaff *et al*., 2018).

From a socio-economic standpoint, population growth and changing consumption patterns put growing pressure on limited land, water and energy supplies to meet food, material and energy demands (Elsayed *et al*., 2020). As populations and economies develop, diets tend to shift towards more resource-intensive livestock products, exacerbating competition over land and agricultural inputs (Mohtar and Rosen, 2015). Access to these interconnected resources also influences livelihoods, health, education, gender equality and poverty reduction (Kumazawa *et al*., 2017).

Climatic variations further impact the nexus through changes in rainfall patterns, temperatures and extreme events frequency. For example, prolonged droughts affect crop yields, reservoir levels and energy production capacities from hydropower (Nhamo *et al*., 2020). Climate change can therefore undermine progress on food, water and energy security if resilient nexus-based solutions and adaptation measures are not adopted (IPCC, 2021).

From a policy perspective, separate sectoral and fragmented governance of these issues impedes an integrated nexus approach (Endo *et al*., 2017). Management is often conducted at administrative scales which do not correspond to natural resource basins boundaries (Kumazawa *et al*., 2017). Trade-offs between short-term sectoral priorities also hamper the consideration of cross-scale and long-term systemic impacts in decision-making (Mohtar and Rosen, 2015).

Recent efforts have been made to address these challenges. For instance, various countries and regions developed tools and processes to assess interlinkages within their Nationally Determined Contributions to the Paris Agreement (Paim *et al*., 2020). Multistakeholder working groups also aim to foster collaborative nexus governance cutting across silos (Akinsete *et al*., 2022). However, integrated nexus planning and coordination of policies remains limited compared to the scale of issues at stake.

2.1.3. Nexus WEF Technologies

- **Water**

Intelligent farming systems enable optimized resource management in the WEF nexus. ***Drip irrigation coupled with fertigation using greywater*** increases feed productivity while saving water and fertilizers, with yields increased by 20-90% (Dordoni *et al*., 2021). This technology has demonstrated its relevance for intensive maize cultivation in Mexico and cotton in India (Jadhav et *al*., 2021; Juárez-Torres *et al*., 2021). ***Precision agriculture*** optimizes inputs via sensors and drones that accurately measure the water and nutrient needs of crops (Gebbers & Adamchuk, 2010). In the United States, ***satellite-guided irrigation pivot systems*** save up to 30% of water on corn and wheat by applying it only according to the actual needs of the plants (Shannon *et al*., 2018). Underground sensors also detect areas with low water or nutrient content to target inputs (Dong *et al*., 2020). Similarly, ***market gardening under water-saving shelters, such as greenhouses and soilless cultivation***, is developing. ***Hydroponics*** increases yields 5-10 times while saving 90% of water compared to traditional methods (Rahman *et al*. 2019).

- **Energy**

On the energy side, agrofuels represent a synergistic solution, in particular lignocellulosic biomass from agricultural residues. In Brazil, sugarcane bagasse is used to power plants that cogenerate heat, electricity and fuel, recovering waste while securing energy supply (Goldemberg *et al*., 2020). Algae can also play this role, concentrating 10 times more energy than land-based crops, such as in Morocco where their production provides biodiesel and fertilizes the soil (Ilham *et al*., 2021). ***Concentrated Solar Power Plants*** (***CSPs***) using mirror fields that follow the movement of the sun heat a heat transfer fluid feeding a steam turbine to produce electricity (Tian & Zhao, 2013). Installed on degraded land in China, they regenerate soils while producing green energy and sequestering carbon (Ma *et al*., 2019). ***Agrivoltaic greenhouses*** combine cultivation and photovoltaic panels on the same floor space, protecting crops from water stress and producing 2 to 3 times more electricity per hectare than dedicated facilities (Jagadeesh *et al*., 2014).

- **Agriculture**

The anaerobic digestion of agricultural residues and livestock manure to produce biogas is a key sector in the energy and food transition (Cross *et al*., 2021). In India, individual ***biodigesters*** transform cattle manure into cooking gas, reducing deforestation linked to wood energy by 80% while adding value to this resource (Prasad *et al*., 2017). With nearly 800,000 units installed, India is the world leader in this field (Singh & Sooch, 2004). In Mexico, anaerobic digestion of unsold fruits and vegetables avoids their waste and produces bioCNG for transport (Ortiz-Moreno *et al*., 2021).

2.1.4. Nexus approaches and principles

There are different approaches that have been proposed to study and address the water-energy-food nexus in an integrated manner based on certain key principles. Accounting frameworks aim to quantitatively assess resource use and flows within and between sectors. For example, the Water-Energy-Food Nexus Index developed by Simpson *et al*. (2020) aggregates 32 indicators into a single score for over 100 countries. It revealed vast disparities in nexus sustainability, from values of 65+ in developed countries versus 25- in Africa/MENA. Physical input-output models also represent technical flows to analyze interdependencies (Elsayed *et al*., 2020). The Nile Nexus Model developed for Ethiopia, Sudan and Egypt involves over 190 water and energy parameters.

Scenario-based approaches explore future nexus trajectories based on alternative assumptions regarding policy levers, climatic or socio-economic changes. For instance, Elsayed *et al*. (2022) modeled Grand Ethiopian Renaissance Dam reservoir filling scenarios to study transboundary impacts on water availability, irrigation and hydropower in Eastern Africa. The inclusion of uncertainty ranges acknowledged limited predictability. Stakeholder-centered approaches recognize the human dimension through participatory processes. Working groups help integrate local knowledge and priorities into decision-making (Akinsete *et al*., 2022). Serious games also foster social learning and consensus-building on potential responses (Vamvakeridou-Lyroudia *et al*., 2017). The SIM4NEXUS game involved over 500 participants in Sardinia. Model-frameworks like the one developed by Nhamo *et al*. (2020) aim to systematically structure nexus understanding. It combines biophysical modeling of trade-offs with analysis of food security, livelihoods and policies. Regardless of method, certain principles apply across nexus work. These include considering the system holistically rather than individual sectors, acknowledging cross-scale interdependencies from local to global, adopting long-term perspectives, prioritizing sustainability over narrow sectoral gains, and adapting through iterative risk/vulnerability assessments. Adherence to these serves to mainstream the nexus from analysis into decision-shaping.

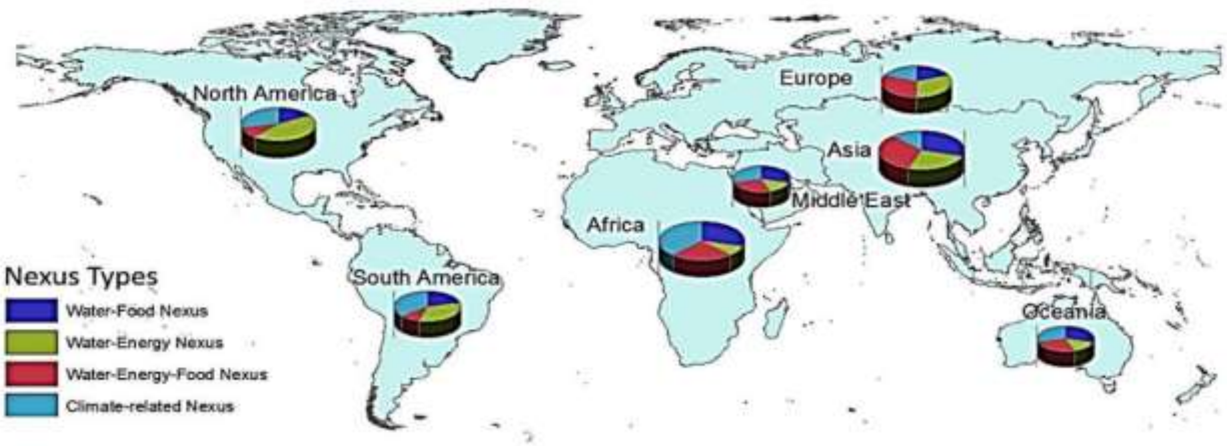


Figure 2: A graphical presentation of nexus types in different regions. (Source : Endo *et al*., (2017))

2.1.5. Application of the nexus in the African context

The water-energy-food nexus is particularly relevant for sub-Saharan Africa given the region's high dependence on natural resources and vulnerability to climate impacts. Several studies and initiatives have applied the nexus approach in African contexts.

A key driver is Africa's population growth projected to reach over 2.5 billion people by 2050, increasing demands on limited resources (UN, 2022). Already, over 250 million Africans remain food insecure (FAO, 2022). Achieving the SDGs of zero hunger, affordable energy, and water/sanitation by 2030 presents immense challenges.

Nexus assessment frameworks have evaluated continental sustainability. Using the Water-Energy-Food Nexus Index, Simpson *et al*. (2020) found 15 African nations scored in the lowest cohort, with DRC and Chad at 24/100. Weak governance, resource depletion and climate risks scored poorly. Regionally-disaggregated data is lacking but could enhance context-specific planning.

National studies address context-specific interlinkages. In South Africa's Limpopo River Basin, Makurira *et al*. (2019) modeled crop-livestock interactions, revealing land and water competition vulnerabilities exacerbated by recurrent droughts affecting over 500,000 people. Similarly in Morocco, Bazzaz *et al*. (2022) assessed irrigated agriculture's dependence on depleting fossil groundwater alongside socioeconomic impacts on 350,000 farmers.

Transboundary analyses foster cooperative management. Elsayed *et al*. (2022) modeled the impacts of Ethiopia's Grand Renaissance Dam on cross-border water and energy flows. Benefits include low-carbon hydropower for 60 million Ethiopians/Egyptians/Sudanese but reservoir filling must consider downstream irrigation needs for over 300,000 hectares in Sudan and Egypt.

Stakeholder engagement is vital given complex community relationships with resources. In Somaliland's Togdheer region nomadic pastoralists, farming and mining groups' water interests were analyzed through a SIM4NEXUS serious game engaging 530 participants (Vamvakeridou-Lyroudia *et al*., 2017). Collaborative solutions incorporated indigenous and local knowledge systems.

Finally, Africa's climate vulnerability drives nexus-based adaptation. Nhamo *et al*. (2020) proposed a Southern Africa modeling framework incorporating precipitation projections. This quantifies food security threats to over 220 million people from compound climate change impacts requiring nexus-based climate-resilient policies.

In summary, nexus framing has proven critical to comprehensively address Africa's interconnected sustainable development, climate adaptation, water and energy governance challenges through evidence-based, participatory planning and cooperation on shared resources. Continued application supports achievement of Agenda 2030.

2.2. Climate change impacts and challenges in Sub-Saharan Africa

2.2.1. Observed and projected climate impacts

Climate change poses major risks to the water-energy-food nexus through observed and projected hydroclimate impacts.

Rising temperatures: Most of Africa experienced warming of 0.5-1.0°C over the 20th century, and temperatures are projected to rise 2-4°C by 2100 under business-as-usual emissions (Niang *et al*., 2014). Heatstress already reduces yields for rainfed crops in e.g. South Africa, affecting over 2 million farmers (Thiombiano *et al*., 2019).

Changing rainfall patterns: Declining and more variable rainfall is observed across much of Africa (Niang *et al*., 2014). By 2030, maize production potential is projected to fall 10-20% in parts of Ethiopia, Tanzania and South Africa due to rainfall changes, threatening over 30 million people's food security (Byers *et al*., 2018).

Worsening droughts: Analysis of precipitation data since 1900 found the frequency and severity of droughts increased across southern and eastern Africa (Trenberth *et al*. 2014). Multi-year droughts are projected to escalate, with consecutive dry years expected to occur up to 4 times more often by 2100 in e.g. Zambia under RCP8.5, disrupting hydropower generation for over 1.6 million people (Zhou *et al*., 2021).

Flooding: Heavy rainfall and flooding risks are generally rising. Over 1000 people died during the 2007 floods in Ghana, causing damages of $956 million which comprised 6% of GDP (Owusu and Waylen 2009). Projected future increases in floods and landslides threaten critical water supply and irrigation infrastructure across west Africa (Niang *et al*., 2014).

Sea level rise: Coastal populations in Africa facing sea level rise projected at 0.5-1m by 2100 exceed 120 million people (Weaver *et al*., 2018). Saltwater intrusion already degrades freshwater aquifers and destroys fertile delta farmland in e.g. Niger, impacting 500,000 people's livelihoods (Fregene, 2021).

These impacts already undermine rural livelihoods, energy security and national GDP across the continent. Most impacted are rain-fed and subsistence farmers where over 500 million people derive livelihoods. Evidence stresses the urgent need to adopt climate-resilient, nexus-based solutions at scale to support adaptation.

2.2.2. Vulnerability of water, energy and food resources

Climate change exacerbates existing vulnerabilities in Africa's water, energy and food sectors through nexus linkages.

Water resources: Rising temperatures increase evaporation from soils and open water bodies, reducing available surface and groundwater resources. By 2030, parts of Ethiopia, Tanzania and

South Africa could see overall declines of 5-20% in accessible water due to higher temperatures (Strzepek *et al*., 2013). This poses risks for the over 250 million Africans reliant on rainfed agriculture. Over 300 transboundary river and lake basins leave many countries highly dependent on upstream flows. Infrastructure deficits and unequal distribution also challenge access - only 66% of sub-Saharan Africans use safely managed drinking water (WHO-UNICEF JMP 2021). Climate change amplifies these stresses:

- Rising temperatures increase evaporation from reservoirs, reducing hydropower capacity and water storage for agriculture in basins supporting over 300 million people like the Nile, Zambezi and Senegal Rivers (Dai *et al*., 2018).
- Altered rainfall erodes groundwater recharge crucial for 86% of Africa's rural populations where supplies are already falling in parts of South Africa, Niger, Kenya and Tunisia (Taylor *et al*., 2013).
- Coastal aquifer salinization affects freshwater for over 30 million people as seawater intrudes further inland in areas like the Nile Delta due to sea level rise (Wada *et al*., 2022).

Energy: Reduced River flows from warming and irregular rainfall jeopardize hydropower generation which supplies over 70% of renewable power in countries like the DRC, Ethiopia, Tanzania and Zambia (IEA, 2021). Analysis found hydropower output in the Zambezi basin alone could decrease 12–27% by 2050 under RCP8.5, disrupting access for over 40 million people (Kumar *et al*., 2016). The vast hydropower potential of over 350,000 MW cannot be developed due to inconsistent rainfall. Already, electricity access lags at 43% and relies heavily on distributed diesel generation (IEA, 2021). Low flows cripple hydropower:

- Recurring droughts between 2015-2020 reduced output 10-50% at plants in Ethiopia, Angola, Mozambique and Namibia depending on dam storage capacities (Berga, 2016).
- Under RCP8.5 by 2100, the average electricity generation weighted by installed capacity could fall 5–40% in Eastern and Southern Africa as droughts and floods worsen (Zhou *et al*., 2021).
- This subjects over 220 million people to increased electricity prices and supply disruptions which undermine health, education and economic development.

Climate change exacerbates vulnerabilities across Africa's interconnected water, energy and food sectors.

Food: Lower crop water availability, heat stresses and increased pest/disease outbreaks caused yield losses estimated at 22 million tons or 4% of total production across Africa in 2100 under RCP8.5 (Nelson *et al*., 2014). This threatens food security for over 250 million undernourished Africans. Moreover, coastal inundation and salinization due to 0.5-1m sea level rise risks displacing over 120 million people and submerging 1.8 million hectares of farmland, mostly in West Africa (Vousdoukas *et al*., 2020).

Livestock: Warming, disease shifts and variability in forage/water access linked to climate additionally jeopardize the livelihoods of over 600 million Africans dependent on livestock rearing (Thornton *et al*., 2009). For example, recurrent drought has contributed to over 50% losses in herd sizes among pastoralists in the ASAL rangelands of Kenya, impacting 400,000 families (KNBS, 2015).

Integrated water-energy-food adaptation is crucial, especially through decentralized renewable energy, climate-smart agriculture, early warning systems and transboundary cooperation frameworks (IPCC, 2022). These helps strengthen nexus security in the face of compounded threats from climate change.

2.2.3. Sensitivity of agriculture and food security

Africa's agriculture and food security face severe risks from climate change, exacerbating existing vulnerabilities:

Crop yields: Maize, wheat, rice and sorghum yields are projected to decline 5-20% across much of Africa by 2050 due to warming and rainfall changes alone (Nelson *et al*., 2010). Studies across 11 countries found yields have already fallen over recent decades in 80% of crops assessed, including 10-25% potato yield losses in Rwanda and Burundi (Schlenker & Lobell, 2010).

Livestock: Milk production from cattle is very sensitive to temperatures, with over 5% declines projected for East Africa and parts of southern Africa by 2050 due to heat stress (Thornton *et al*., 2009). Livestock mortality also rises - millions of livestock deaths occurred during the 2015/16 El Niño drought affecting over 11 million Kenyans (FAO, 2017).

Staple crops: Domestic production shortfalls increase reliance on imports of key African staples like maize, rice and wheat. By 2050, maize yields could fall 30% in parts of South Africa, reducing self-sufficiency and increasing import needs for over 60 million people (Laurance *et al*., 2014).

Smallholders: Nearly 80% of the 525 million food insecure Africans depend on vulnerable rain-fed smallholder farming highly exposed to climate hazards (IFAD, 2017). Recent drought in southern Africa led 80% of 120,000 surveyed small-scale households to deplete livelihood assets like livestock (WFP, 2020).

Post-harvest: Changing patterns also damage stored staples - over 30,000 tons of maize was lost to elevated mould risks during unusual 2016 rainfall in Tanzania, compromising supplies (GRAIN, 2016). Aflatoxin poisoning from pathogenic fungal growth linked to warming threatens food safety.

Climate-resilient agriculture is paramount to sustain Africa's food production which currently feeds over 1.2 billion people (AUDPC, 2021). adaptation and social protection programs are critical.

2.2.4. Adaptation issues in key sectors

Climate change adaptation is crucial across Africa's water, energy and food sectors given the continent's exposure and vulnerabilities. However, several issues must be addressed to enhance resilience.

Water sector adaptation requires expanded storage and irrigation infrastructure to buffer climate variability impacts. However, sub-Saharan Africa's irrigation potential is only utilized at 4%, with high development costs limiting progress despite benefits for over 300 million farmers (You *et al.*, 2011). Affordability also challenges many countries' ability to invest an estimated additional $15 billion annually needed for climate-proofing water systems (UNEP, 2016).

In energy, uptake of renewables like small-scale solar is hindered by the relatively high upfront costs which can still exceed 30% of household income in rural Africa versus global averages of 10% (IEA, 2021). Storage remains a major technical hurdle despite potential for off-grid solutions to serve over 600 million people lacking electricity (IEA, 2021). Limited regulation and uneven resource endowments also impede wider regional power pooling as an adaptation strategy (IRENA, 2019).

For food and agriculture, forecasted yield declines threaten food security for over 250 million undernourished Africans heavily reliant on rainfed crops. However, scaling up climate-smart practices faces challenges from low uptake rates of just 5-10% for introduced drought-tolerant varieties, conservation farming techniques or livestock herd diversification (FAO, 2017). Outdated extension services remain ill-equipped to boost adoption by over 120 million African smallholders (Wani *et al*., 2009).

Developing climate information services also requires investments estimated at $500 million to cover monitoring gaps and support sector planning, early warning and index insurance schemes (UNECA, 2016). Even where data exists, access and literacy challenges undermine use by over 80% of the population in many countries (Tall *et al*., 2014).

Overcoming these barriers demands reinforced policies, investments, capacity building and regional partnerships. Nexus coordination across sectors could aid integrated solutions tailored to diverse African needs.

2.3. Integrating the nexus in climate policy

2.3.1. Roles of NDCs and NAPs for climate action

Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs) are key mechanisms for African countries to outline climate actions and strengthen resilience under the Paris Agreement. They offer opportunities to integrate nexus-based approaches.

NDCs: All 55 African states have submitted first NDCs, with 40 updating them by early 2022 (UNFCCC). Collectively these aims to curb emissions 25-45% below baseline by 2030 (UNEP, 2021). Most prioritize renewable energy expansion and improved cookstoves, with potential for nexus co-benefits. However, limited industrialization means Africa contributes only 3% of global emissions despite hosting 17% of the world's population, emphasizing greater focus on adaptation needs.

NAPs: By 2020, 38 African countries developed initial NAPs outlining priority adaptation actions across sectors (UNEP, 2021). Water, agriculture, health and ecosystems featured prominently given sensitivity to climate hazards. integrated approaches were recognized in documents from Mali, Ethiopia and Morocco incorporating linkages between water and food security, yet implementation pathways require strengthening (Dieng *et al.*, 2021). Only 10% of planned public adaptation investments in African NDCs and NAPs were internationally supported by 2019, highlighting major funding shortfalls (UNEP, 2020).

Nexus in climate planning: Countries are increasingly mainstreaming interlinkages between sectors. South Africa's NDC and NAP both address water security, energy production disruptions and climate risks to agriculture supporting an estimated 60 million livelihoods (South Africa, 2021). Kenya coordinates actions for agriculture, livestock, water provision and renewable energy development across 32 ASAL counties where over 10 million depend on climate-sensitive grazing lands (Kenya, 2021). Coordinated implementation and evaluation across NDCs, NAPs and larger development frameworks remains challenging however.

Synergies abound to enhance coherence if African nations receive the estimated $130 billion in annual investment required for full implementation (UNECA, 2018). Nexus-informed planning strengthens climate resilience while supporting sustainable development across interconnected sectors. Robust finance and partnerships will be vital to realize this potential.

2.3.2. International examples of nexus mainstreaming

Japan incorporated nexus considerations into its updated 2030 NDC through sustainable agriculture and renewable energy development policies. Measures aim to increase food self-sufficiency by 5% by 2030, benefiting over 1 million farmers (MoE, 2021). The European Union's 2018 Bioeconomy Strategy highlights the nexus potential of bioenergy and circular bioeconomy to advance sustainability across food, water and energy sectors for its 28 member nations (EC, 2018). It facilitates multi-actor partnerships. California instituted a 2021 "Roadmap" coordinating climate-smart actions across state agencies for agriculture, water management, energy and natural systems. Goals include boosting drought resilience for over 500,000 farms and incentivizing climate-friendly diets (CA WEF Nexus, 2021). The Mekong River Commission facilitates nexus dialogue among Cambodia, Laos, Thailand and Vietnam on hydropower development, irrigation and fisheries/biodiversity conservation across its 660,000km^2 basin sustaining over 70 million livelihoods (MRC, 2019).

Germany's National Policy Strategy on the Nexus explores policy levers to realize intersectoral opportunities through stakeholder platforms, research initiatives and international partnerships (BMZ, 2017).

The US National Intelligence Council's Global Trends report emphasizes the security risks of unmanaged competition over water, energy and land resources, stressing the need for cooperative management approaches (NIC, 2017).

These examples showcase replicable multilevel governance, stakeholder involvement, cross-sector coordination, research-policy links and global collaboration in mainstreaming the nexus into climate strategies and planning.

2.3.3. Interactions between climate and development policies

Climate change threatens to undermine international development goals like those enshrined in the UN 2030 Agenda unless resilient pathways are established. Integrating climate and development policies presents opportunities to strengthen coherence through a nexus lens.

The IPCC highlights climate action as an indispensable enabler for poverty reduction, with over 120 million Africans at risk of being pushed into extreme hardship by 2030 due to impacts (IPCC, 2022). Conversely, sustainable development can support greater ambition in climate strategies through co-benefits. NDCs and NAPs aim to deliver on both the Paris Agreement and SDGs. Analysis found potential for African NDCs alone to contribute 27-47% towards achievement of certain SDGs relating to energy, water and food security if fully implemented (UNEP, 2021). However, financing remains a core constraint, with adaptation costs in developing countries estimated at $140-300 billion annually by 2030 (UNEP, 2016).

Mobilizing climate finance thus demands aligning investments from development banks, aid and the private sector with priorities featured prominently in NAPAs, NAPs and NDCs. The African Development Bank pioneered an SDG alignment index to systematically assess over 500 projects in this regard across 53 nations (AfDB, 2019).

Policy instrument interactions can also be strengthened through integrated strategies like the EU's forthcoming 2030 Climate Adaptation Strategy intended to coordinate sectoral planning with the European Green Deal achieving emission cuts of 55% by 2030 (EC, 2021).

Nexus dimensions similarly promote mutually reinforcing linkages between climate objectives in NDCs/NAPs and SDG targets for water, energy access, food security and terrestrial ecosystems involving over 350 million smallholder farmers who must cope with changing conditions (FAO, 2019).

Coordinating mechanisms are required nationally and regionally to maximize synergies - for example the African Union's Agenda 2063 coordinates continent-wide actions simultaneously pursuing socioeconomic transformation and climate resilience priorities through its First Ten-Year Implementation Plan (African Union, 2013).

Systemic integration can help address projected climate impacts confronting over 350 million vulnerable African livelihoods through climate-smart solutions aligned across climate and development frameworks.

2.4. Benin context

2.4.1. Water, Energy and Agricultural Resources in Benin

- **Water Resources**

Benin's water resources comprise several vital river basins. The Ouémé basin is the largest, covering over 30,000 km² across the country from north to south before emptying into the Gulf of Guinea (FAO, 2021). It provides drinking water to over three million people and supports important irrigated farming, notably rice cultivation. The Couffo basin is also significant, traversing central-southern Benin over around 9,000 km^2 prior to joining the Ouémé, sustaining agriculture and livestock in this region. The smaller Zou basin of approximately 3,000 km^2 is located in west-central Benin and drains the Allada area. Collectively, these river basins constitute Benin's primary water source for over five million inhabitants, with high dependence on their endowments (UNDP, 2021).

However, Benin faces mounting challenges of water stress. Annual water availability per capita stands at a meagre 687m^3, far below the 1000m^3/capita/year threshold indicative of water scarcity defined by the UN (UNDP, 2021). This stems from rising demand from agriculture, industry and households against degrading resources. Rainfall, though fluctuating regionally from 1100-1500mm/year, exhibits general declines due to climate change (GWP, 2009). Furthermore, rampant urbanization and inadequate wastewater treatment increasingly pollute surface and groundwater supplies. Accelerated soil erosion owing to deforestation also diminishes water retention capacity. Overall, accessing sufficient quality and quantity of water is becoming problematic for Benin's populace and economy.

- **Energy Resources**

On the energy front, Benin faces considerable hurdles in meeting the needs of its fast-growing population. While possessing hydropower potential estimated at circa 148MW, less than 5MW is currently harnessed due to heightened rainfall variability (IRENA, 2019). The bulk of supply derives from fuelwood and charcoal, accounting for 91% of the country's primary energy output according to the World Bank. This extreme dependence on traditional biomasses substantially contributes to deforestation, with forest cover falling to a meagre 34% by 2015.

Merely 19% of Benin's population has electricity access, predominantly in urban centres. Rural electrification rates lag below 10%, with non-grid households reliant on kerosene lamps and diesel generators (IEA, 2021). Solar irradiation averages around 5kWh/m^2/day, yet renewable energy development remains nascent, with less than 5MW combined of wind and solar installed by late 2020. Benin hence remains heavily reliant on imported petroleum products for thermal power generation despite oil price volatility risks.

- **Agriculture**

Agriculture constitutes an essential pillar of Benin's economy, accounting for approximately 26% of GDP and two-thirds of labor force employment. Most farms are small-scale holdings of under 5 hectares with low mechanization levels. Key crops in the north include maize, cassava, yams, cowpeas and groundnuts, while the south additionally cultivates oil palms, cotton, pineapples and plantain (FAO, 2021). Livestock rearing of cattle, sheep and goats complements rural livelihoods.

However, the agricultural sector exhibits high dependence on climate vagaries in the absence of widespread irrigation. Prolonged rainfall declines observed in the arid north over recent decades have induced millet and sorghum yield losses of 3-10% annually, jeopardizing food security (USAID, 2015). Along the southern coastline, increasing soil and aquifer salinization due to sea level rise severely compromises dominant rice production (UNECA, 2018). Overall, Benin's predominantly rain-fed agricultural system exhibits deep structural vulnerability to climate change impacts, particularly threatening food security for the largely rural population.

2.4.2. Interdependencies across sectors

Benin's water, energy, food and other socioeconomic sectors exhibit close interlinkages that have significant implications for pursuing integrated climate adaptation and development.

Water resources underpin agriculture, which accounts for over 60% of water withdrawals globally (FAO, 2022). In Benin, rain-fed smallholder farming dominates production, with over 80% of the population dependent on climate-sensitive agricultural livelihoods (IFAD, 2017). Climate change impacts like declining and more variable rainfall patterns threaten crop and livestock production across the country, compromising both rural and national food security (USAID, 2015). At the same time, increased withdrawals for irrigated agriculture are exacerbating water stress, requiring optimized water management.

Energy generation is also tightly coupled with water availability. Hydropower currently supplies a small yet indispensable fraction of Benin's energy needs but output is constrained by decreased and unpredictable rainfall (IRENA, 2019). Thermal electricity production from gas, coal and oil meanwhile places growing pressure on limited water stocks for cooling (IEA, 2021). As renewable options like solar gain traction, their energy-water nexus aspects must be factored into long-term planning.

Food systems in turn shape energy security through agriculture-based biofuel and biomass use. Over 90% of Benin's population relies on fuelwood and charcoal for cooking, accentuating deforestation and degradation risks to fragile woodlands (FAO, 2021). However, judicious development of modern agro-energy value chains could provide rural livelihood opportunities while diversifying the energy mix. Hybrid approaches integrating bioenergy with improved cookstoves show potential.

Environmental health intersects all sectors and underscores climate resilience. Depleted forests hamper watershed protection, increasing siltation and floods downstream (GTZ, 2008). Salinization of aquifers and agricultural lands near coastal cities represents a mounting threat under rising seas and groundwater over-pumping (UNECA, 2018). Sustainable land and water governance will be critical for people's well-being as climate hazards intensify.

Strong sectoral interconnections in Benin highlight the need for coordinated climate action bridging development priorities. Integrated adaptation planning offers opportunities to capitalize on resource nexus synergies while building a greener, more equitable and climate-resilient future. Cohesive partnerships across government, communities and stakeholders will thus be imperative to effectively address complex, intertwined challenges.

2.4.3. Prioritized climate issues in national documents

Benin's National Adaptation Programme of Action (NAPA) submitted to the UNFCCC in 2006 constitutes its major national document outlining top climate priorities (GoB, 2006). It identified 4 urgent sectors requiring adaptation support – agriculture and food security, water resources, coastal areas and public health.

Agriculture and food security featured most prominently given the sector's dominance in GDP, employment and sustenance of over 80% of Benin's rural population (FAO, 2020). Key projected impacts include declining crop yields from increased heat stress and irregular rainfall trends threatening food production across maize, cassava and yam belts. Coastal salinization also jeopardizes rice farming livelihoods. The NAPA prioritized introducing drought-tolerant and saline-resistant varieties, alongside climate-smart agriculture practices such as agroforestry, conservation farming and improved irrigation.

Water resources topped the NAPA due to the country's water stress status and dependence on surface flows and groundwater for domestic, agricultural and industrial uses. Climate hazards like more frequent droughts and floods endanger water supplies for over 6 million residents (UNICEF, 2018).

Priority measures included integrated water resources management, rainwater harvesting, and rehabilitation of degraded watersheds.

Coastal areas ranked highly owing to exposed livelihoods and infrastructure along Benin's 120km shoreline. Threats involve saline intrusion into freshwater lenses, erosion exacerbated by sea level rise and saltwater inundation during storms (UNEPO, 2018). The NAPA prioritized nature-based solutions like mangrove restoration, hard protections in at-risk urban zones and relocation of vulnerable communities.

Public health was a fourth strategic sector as disease burden will increase with climate-influenced factors such as food and water insecurity (WHO, 2016). Prioritized health adaptation needs encompassed early warning disease surveillance, water safety plans and health education.

Benin's Intended Nationally Determined Contribution (INDC) under the Paris Agreement reiterated these NAPA priorities while expanding mitigation co-benefits (GoB, 2015). A National Climate Change Policy and Strategy was additionally adopted in 2015 to guide low-carbon, climate-resilient development across key sectors like energy, transport, urban areas and ecosystems (GoB, 2015). These national instruments demonstrate Benin's acknowledgement of imminent climate threats and intention to coordinate holistic adaptation-mitigation responses.

3. OVERVIEW ON THE STUDY AREA, BENIN REPUBLIC

This chapter provides a general overview of the physical, socio-economic, and environmental aspects of Benin.

3.1. Geographical location

Benin lies in the intertropical zone, between latitudes 6°30' and 12°30' North, and longitudes 1° and 3°40' East. It has a total surface area of 114,763 km², and is bordered to the north by Niger and Burkina Faso, to the south by the Atlantic Ocean, to the west by Togo, and to the east by Nigeria. The country is made up of four administrative entities (12 departments, 77 communes, 546 arrondissements and 5,290 villages)(Figure 3).

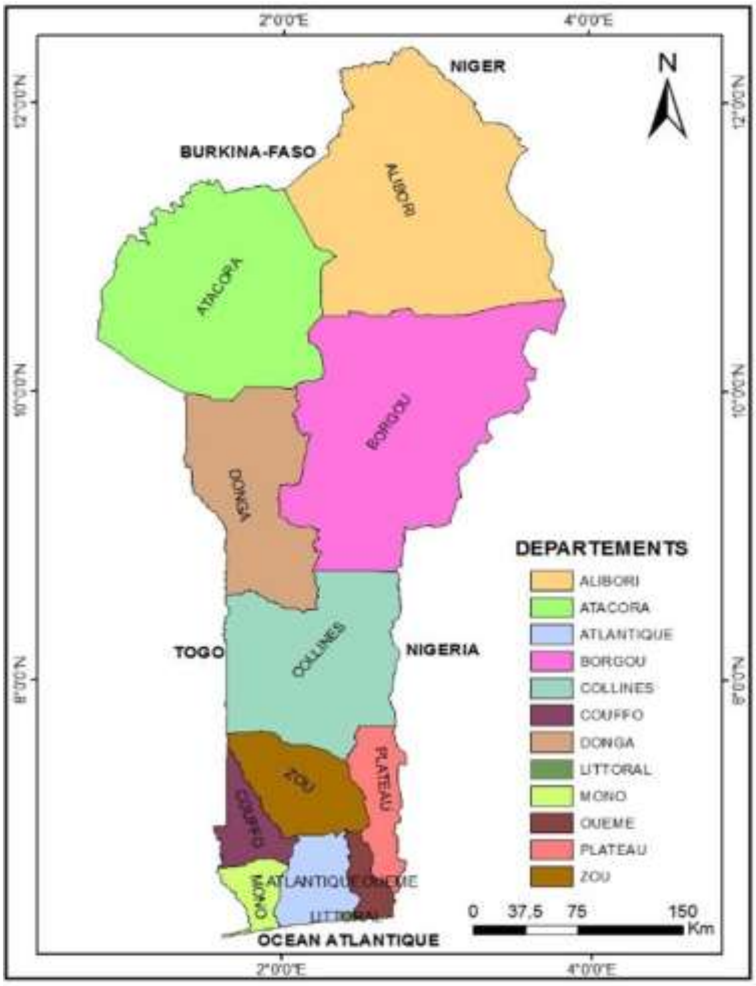


Figure 3: Location of the Republic of Benin (Source: Météo-Bénin, 2022)

3.2 Physical environment

3.2.1. Climatic characteristics

Benin has two (2) types of climate: in the south, an equatorial climate with high humidity and alternating dry seasons (November to March and mid-July to mid-September) and rainy seasons (April to mid-July and mid-September to October).

The center and north of the country have a tropical climate, with a dry season from November to April and a rainy season from June to September. This combination of seasons has given rise to three climatic zones stretching from south to north, namely a Guinean zone, a Sudano-Guinean zone and a Sudanian zone (Figure. 4).

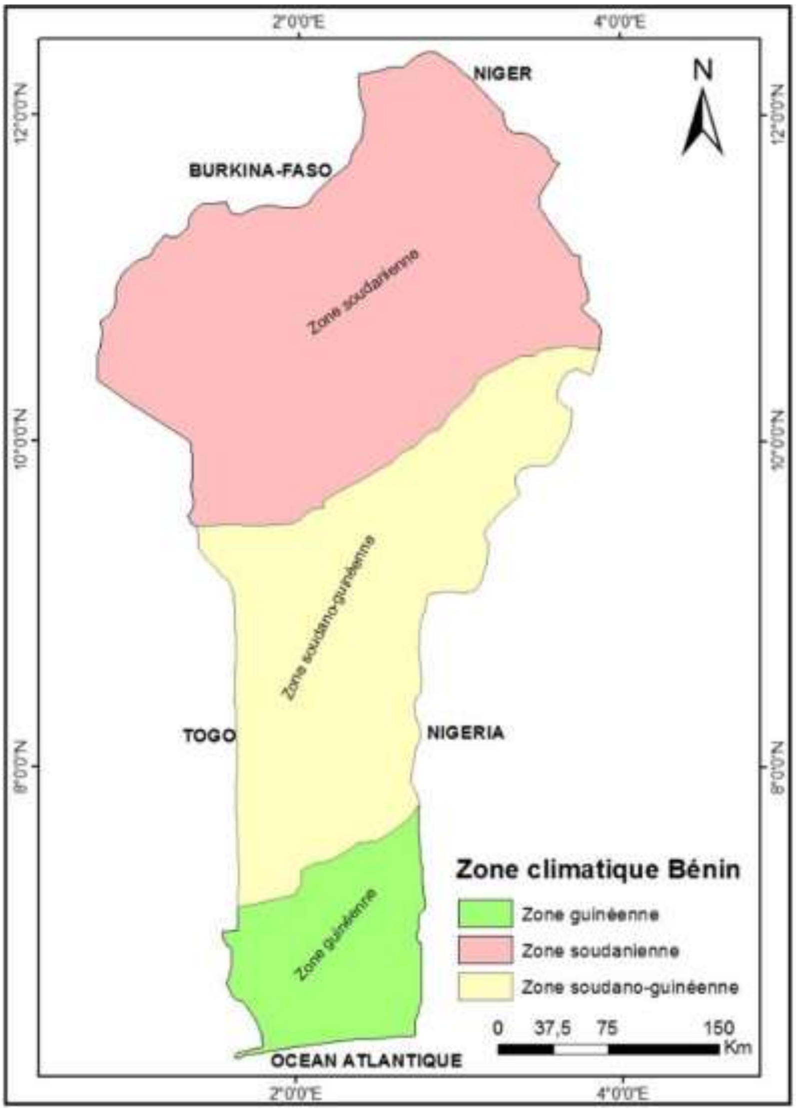


Figure 4: Benin's Climatic Areas (Source: Météo-Bénin, 2022)

In ***the Guinean-Congolese zone***, there are four different seasons. A total of 87 days and 1217.1 mm of precipitation fall on the area each year on average. There is 260.6 mm of rainfall variation between the wettest and driest months. Furthermore, there is a seasonal variance of 3.7°C from the annual average temperature of 27.4°C. The official rainy season is from April to July, however there is a shorter one that lasts from September until mid-November. These wet seasons are interspersed with two dry ones: a lengthy one from mid-November to mid-March and a brief one from August to September. The daily average temperature ranges from 25° to 29°C, while the air humidity ranges from 69% to 97%.

The Sudano-Guinean zone has a rainfall regime that straddles the divide between bimodal and unimodal. Average annual rainfall ranges from 900 mm to 1110 mm, usually averaging 75 days. Relative humidity varies from 31% to 98% in this zone, while temperatures range from 25°C to 29°C. Finally, in the Sudanian zone, rainfall ranges from 900 to 1100 mm per year, averaging 71 days. Air humidity varies from 18% during the harmattan (December to February) to 99% in August during the rainy season. Average monthly temperatures range from 24°C to 31°C.

There is just one season of rain in ***the Sudanian zone***, which is between 9°45 and 12°25 N. The rainy season lasts from June to September, whereas the dry season lasts from November to May. The annual rainfall in this region ranges from 900 to 1100 mm, spread out over an average of 145 days. The range of average monthly temperatures is 24°C to 31°C. The soils are lithosols, hydromorphic, and ferrallitic cuirasses.

3.2.2 Hydrography and Water Resources

According to the Ministry of Agriculture, Livestock, and Fisheries (MAEP) and the Food and Agriculture Organization (FAO), Benin is intersected by various rivers and water bodies (lakes and lagoons) (MAEP/FAO, 2007). These include the rivers Ouémé (510 km), Okpara (200 km), Couffo (190 km), Zou (150 km), Mono (100 km), Pendjari (380 km), Niger (120 km) with its tributaries Mékrou (410 km), Alibori (338 km), and Sota (250 km). Additionally, there are water bodies, primarily composed of lakes Nokoué (150 km^2), Ahémé (78 km^2), Toho (15 km^2), Togbadji (4 km^2), and lagoons Ouidah (40 km^2), Porto-Novo (35 km^2), and Grand-Popo (15 km^2).

Benin is a relatively well-watered country, with an estimated potential of approximately 1.87 billion cubic meters of groundwater and about 13 billion cubic meters of surface water per year (NDC, 2021). This substantial quantity is generated by four major watersheds that span the country: the Beninese portion of the Niger Basin in the northeast (Alibori, Mékrou, and Sota), the Beninese portion of the Volta Basin in the northwest (Pendjari Basin), the Beninese portion of the Mono Basin in the southwest, and finally, the Ouémé and Yéwa Basin (southeast), which occupies the majority of the Beninese territory (Figure 5). In addition to these hydrographic basins, there is the coastal strip, consisting predominantly of wetlands resulting from the low relief (slopes of less than 5%) observed at the continental terminal. This leads to low-lying floodplains that collectively constitute the coastal lagoon complex, comprising lakes and lagoons (MCVDD, 2018).

The country's hydrogeological system is characterized by two major geological formations determining various types of aquifers from which groundwater is extracted. These are the discontinuous aquifers of the predominant basement region and the continuous aquifers of the sedimentary regions, covering approximately 80% and 20% of the total area of Benin, respectively.

The total annual recharge of the different aquifers is estimated at about 1.87 billion cubic meters of water, with an average recharge of 163 cubic meters per hectare for the areas considered. The coastal sedimentary basin, constituting 10% of the total area, holds approximately 32% of the country's groundwater resources (MCVDD, 2019).

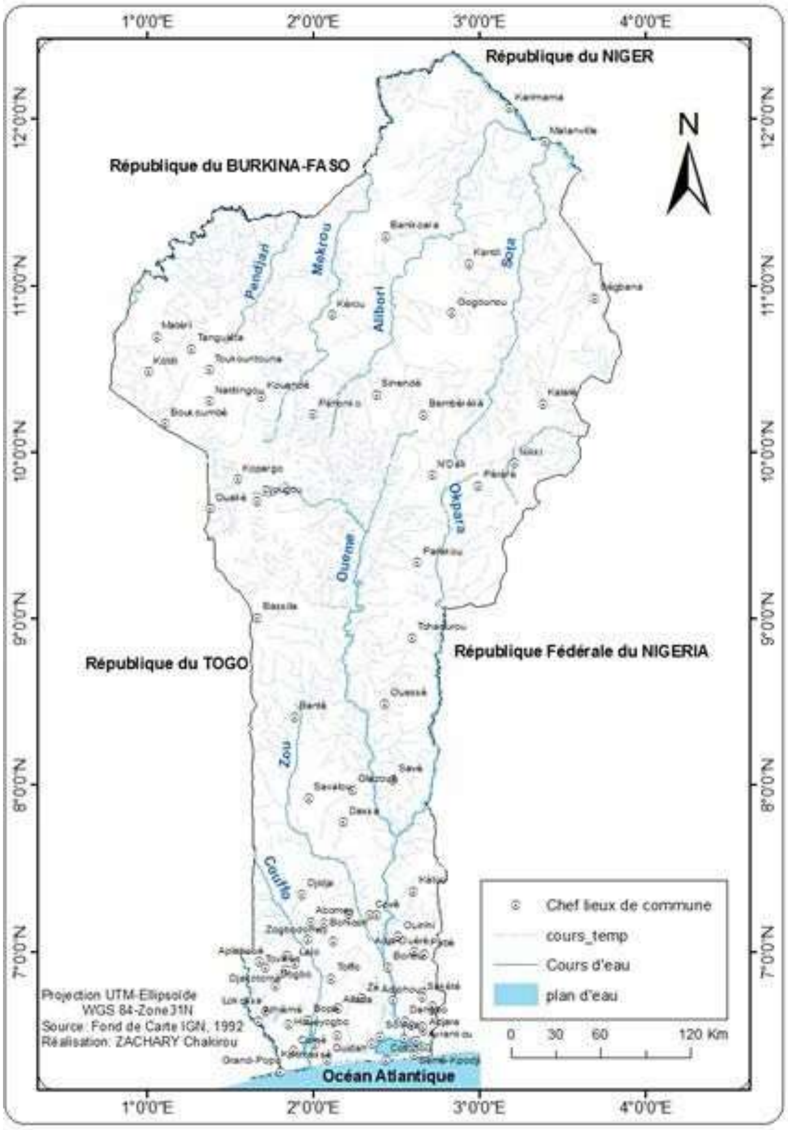


Figure 5: Benin Hydrographic Network (Source: NAP-Benin, 2022)

3.2.3. Pedology and Soils

In general, five main types of soils can be distinguished in Benin (Figure 6), with their geographical distribution from south to north as follows:

• On the sandy coastal ridge, there are raw and underdeveloped mineral soils.

• In the southern sedimentary basin, there are ferruginous red soils formed on the "Continental Terminal."

• In the depression of Lama, which corresponds to a cut made in the southern sedimentary basin exposing Eocene marls and clays, vertisols develop.

• In alluvial valleys and floodplains, hydromorphic alluvial soils, varying from sandy to clayey, are encountered.

• In the central and northern part of the country, on granito-gneissic, granitic, or schistose bedrock, predominantly tropical ferruginous soils, more or less sandy, are formed (NAP-Benin, 2022).

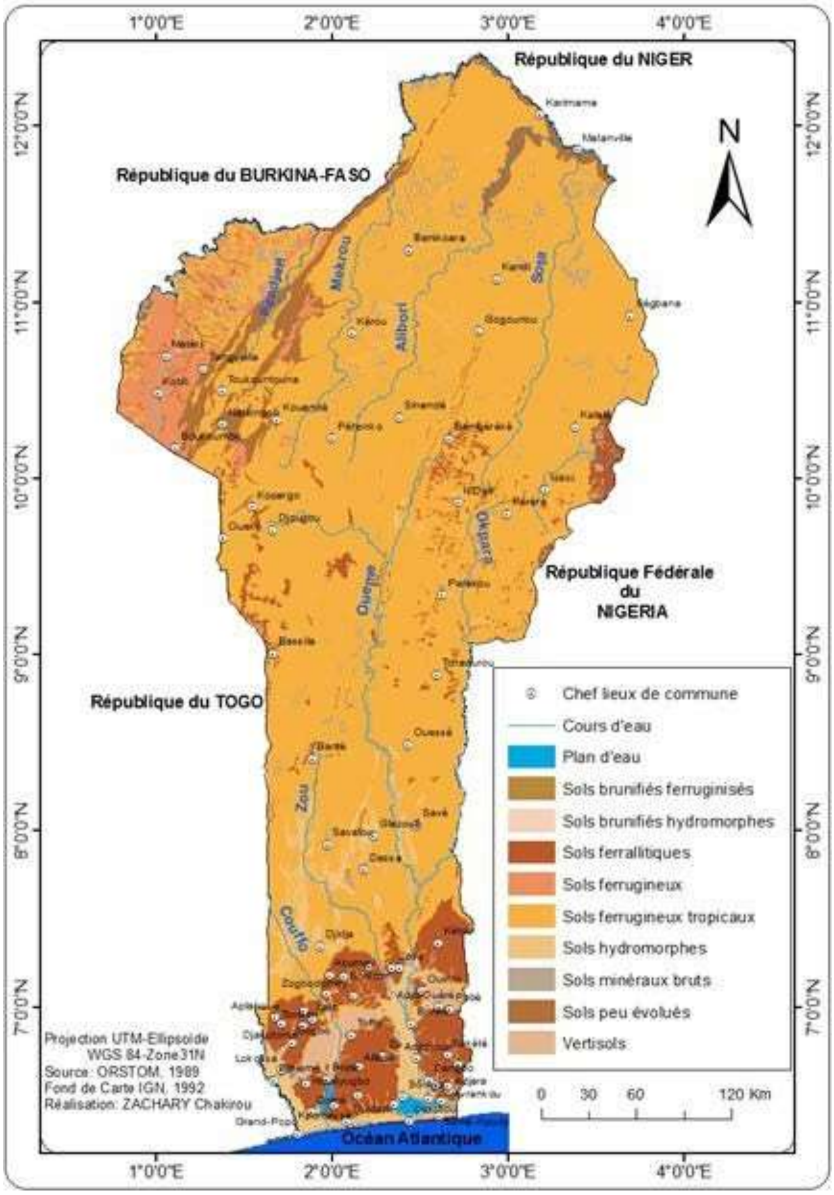


Figure 6: Distribution of the main soil types in Benin (Source : Météo-Bénin, 2022)

The Guinean zone encompasses ferrallitic soils, deep and of low fertility (7,000 km²), alluvial soils, and vertisols (3,600 km²) located in the valleys of the Mono, Couffo, and Ouémé rivers, and in the depression of Lama. These soils are rich in clay, organic matter, and mineral elements. In the transition zone, there are underdeveloped and less fertile mineral soils, as well as ferruginous soils on crystalline bedrock with variable fertility. In the Sudanese zone, the main soil groups encountered include raw and underdeveloped mineral soils on the rocky outcrops of the Atacora Massif, leached tropical ferruginous soils without concretions or rocky elements, leached tropical ferruginous soils with concretions, leached indurated tropical ferruginous soils, and hydromorphic soils.

3.4. Environmental Context

3.4.1. Ecosystems and Vegetation Formations

The Guinean-Congolese zone comprises several ecosystems, including: (i) well-drained soil formations, namely sandy ridges (old or recent); (ii) wetland formations (lagoons and mudflats); and (iii) the original plateau formation consisting of semi-deciduous dense humid forests with remnants in the form of patches (Pobè Botanical Reserve, sacred forests, or relic forests). Key plant species in the Guinean-Congolese zone include *Ceiba pentandra*, *Afzelia africana*, *Diospyros mespiliformis*, *Anogeissus leiocarpus*, *Antiaris toxicaria*, *Milicia excelsa*, *Mimusops andongensis*, *Milicia exelsa*, *Triplochyton scleroxylon*, *Piptadeniastrum africanum*, and *Terminalia superba*.

The southern part of this coastal zone is primarily dominated by hydromorphic entities influenced by specific hydroclimatic and pedological conditions bordering estuarine systems. The vegetation in the West estuary is a mangrove forest reflecting the high salinity of the soils. The climatic formation associated with the East system is a swamp forest consisting of *Symphonia globulifera*, *Mitragyna ciliata*, *Alstonia congensis*, and *Ficus congensis*.

The Sudanese-Guinean transition zone, extending from the Guinean-Congolese zone, exhibits Guinean affinities. It is characterized by mosaics of light forests, occasionally with dense dry forests, interspersed with wooded and shrubby savannas and crossed by forest galleries. In this zone, species like *Daniellia oliveri*, *Parkia biglobosa*, and *Terminalia glaucescens* are found on well-drained soils, *Anogeissus leiocarpus*, *Acacia campylacantha*, and *Terminalia macroptera* on hydromorphic soils, and *Isoberlinia doka* and *Detarium microcarpum* on soils with hardpans or shallow rocks.

The Sudanese zone consists of savannas and forest galleries with trees covering the ground sparsely. In the southern part of this zone, the vegetation is similar to that of the transition zone. Species such as *Isoberlina doka* and *I. tomentosa* are found, followed by *Adansonia digitata*, *Pterocarpus erinaceus*, *Afzelia africana*, *Erythrophleum guineense*, *Amblygonocarpus andongensis*, and *Swartzia madagascariensis*.

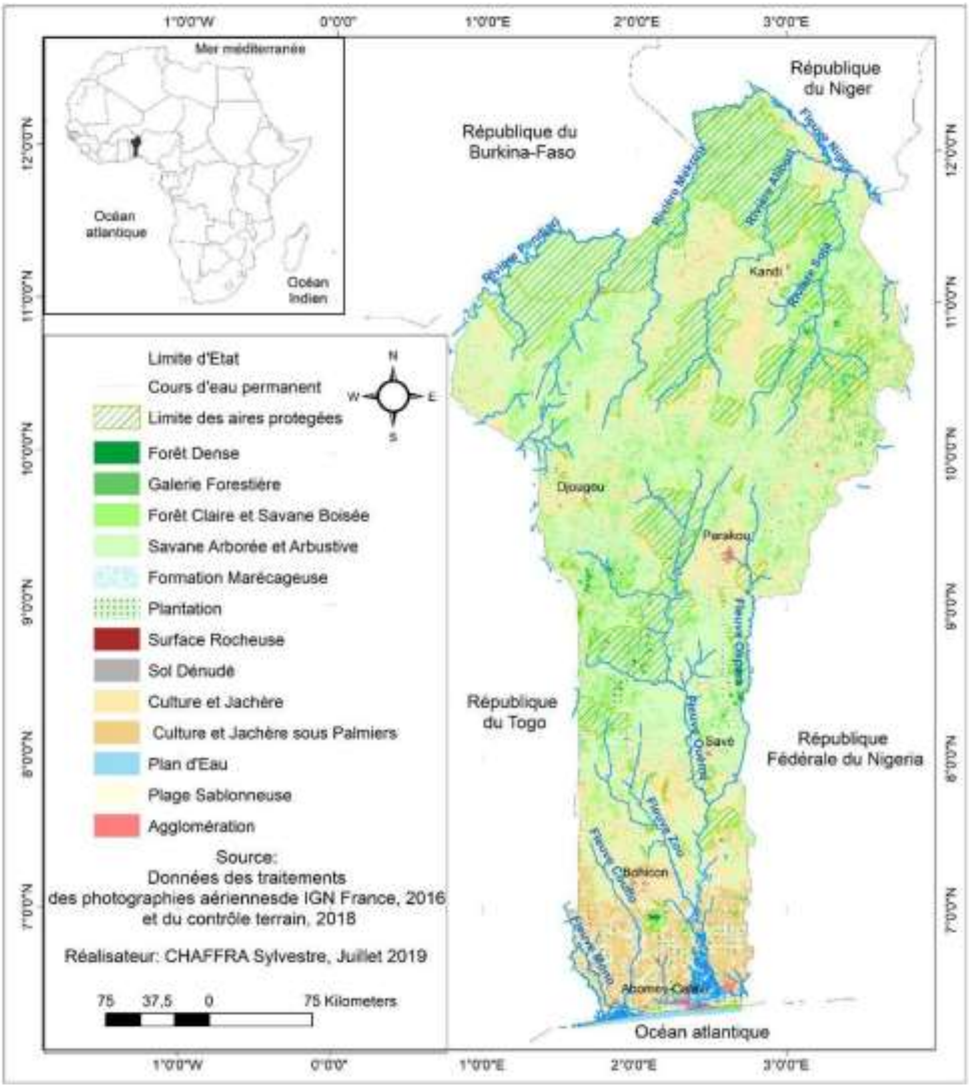


Figure 7: Vegetation formations and land use units in Benin in 2017 (Source: Météo-Bénin, 2022)

3.4.2 Coastal Zone

As defined in Law No. 2018-10 of April 17, 2018, regarding the protection, development, and enhancement of the coastal zone in Benin, in its Article 1, the coastal zone is a geographical entity that includes municipalities:

• Adjacent to the Atlantic Ocean, saltwater ponds, inland water bodies of a certain extent, and directly or indirectly connected to the sea;

• Adjacent to estuaries, deltas, and valleys when located downstream of the salinity limit of the waters and contributing to coastal economic and ecological balances; and

• Non-adjacent to the Atlantic Ocean, saltwater ponds, inland water bodies, estuaries, deltas, and valleys as indicated below but located in the southern part of the plateaus of the coastal sedimentary basin and in the marginal-littoral domain. Figure 6 shows the geographical location of the coastal area of Benin.

On the biophysical level, the coastal area of Benin comprises the coastal plain and the southern plateau domain. The coastal plain exhibits three generations of sandy ridges, either current or inherited, resulting from recent Quaternary marine oscillations (NAP-Benin, 2022). These include internal ridges of yellow sands, median ridges of gray sands, and cu J-rrent and sub-current ridges of brown-gray sand.

The maritime part of the study area is referred to as the Beninese Exclusive Economic Zone (EEZ), extending for 200 nautical miles. It covers an area of 321,424,205 hectares (NAP-Benin, 2022). The continental (terrestrial) part of the study environment consists of the wetlands of South Benin, designated in Ramsar sites No. 1017 and No. 1018, represented by the Southwest Fluvial Lagoon Complex, composed of the lower valley of the Mono River, the Couffo River, and Lake Ahémé, and the Southeast Fluvial Lagoon Complex, composed of the lower valley of the Ouémé River, Lake Nokoué, and the Porto-Novo Lagoon.

The two fluvial lagoon complexes in the south of Benin connect with the Atlantic Ocean through the Grand-Popo estuary known as "Bouche du Roi" (via Lake Ahémé) and the Cotonou channel, 3 kilometers long (via Lake Nokoué).

In the maritime part, two major oceanic forcings influence the coastal zone: swell and tides. The ocean tide is semi-diurnal with extreme tidal ranges of +1.95 m and -0.20 m, with the average amplitude generally revolving around one meter (microtidal type). Swells exhibit two seasons: one with low-height swells (0.4 to 0.5 m on average) from October/November to May; the other, during the boreal summer, from June to September, where wave heights reach and exceed 2 m. Wave directions are constant, showing a predominance of South to Southwest for the first swells and South-Southwest to Southwest for the second. The obliquity of the swell induces a littoral drift current directed from west to east. This current is responsible for the transport of 1.2 to 1.5 million m^3 of sand along the Gulf of Guinea coast (NAP-Benin, 2022).

3.4.3 Social Development Indicators

According to NAP-Benin (2022), the Human Development Index (HDI) of Benin for 2019 stands at 0.545, placing the country in the 158th position out of 189 countries and territories. Benin has progressed by 5 positions in the global ranking. It becomes the first in terms of human development within the West African Economic and Monetary Union (WAEMU) and the third in the Economic Community of West African States (ECOWAS), behind Cape Verde and Ghana. Benin has made progress, especially in health and income domains, with average economic growth rates exceeding 6% in recent years.

Between 1990 and 2019, Benin's HDI increased from 0.364 to 0.545, representing a rise of 49.7%. During the same period, life expectancy at birth in Benin increased by 8 years. The average duration of schooling increased by 2.2 years, and the expected duration of schooling increased by 7.3 years. The country's Gross Domestic Product (GDP) was estimated to have reached 8,814 billion XOF (15.4 billion USD) in 2020, with an estimated population of 12.1 million people. Benin has entered the category of lower-middle-income countries with a GDP per capita of 1,250 USD.

The country's economy is primarily based on agriculture and the processing industries of agricultural products, focusing largely on two export products: cotton and cashew. The primary sector represents 28.1% of GDP, the secondary sector represents 14.6%, including 6% for agro-food industries and 4.4% for the construction and public works sector (CPW). The tertiary sector represents 48.8% of GDP, with 13% for trade and 9% for transportation. Exports, valued at 498 billion XOF in 2019, are highly concentrated on three categories of products: cotton fiber (53% of the country's exports), cashew nuts (9% of exports), and oilseeds (4.7% of exports).

Benin's agriculture is mainly subsistence and almost exclusively rain-fed. It is extensive and shifting cultivation on slash-and-burn, encroaching year by year on the national forest cover. Overall, the main food crops meet the dietary needs of the population but still fall significantly short of the potential offered by the country's ecological conditions.

4. MATERIAL AND METHODS

In this chapter, the methodologies employed to achieve the specific objectives of the study are detailed and have used the quantitative et qualitative approaches. The chapter is structured based on the specific objectives outlined in Chapter 1.

4.1. Material

The tools used for data collection included a WiFi router, laptop computer, notebook for note-taking, and motorcycle for transportation. Software such as Biblioshiny, EndNote, Microsoft Word, and Microsoft Excel were utilized for bibliometric analysis, thesis writing and quantitative data management respectively.

4.2. Methods

4. 2.1. Methodology for Assessing the Interconnectedness of the WEF Sectors

A comprehensive review of existing literature related to the WEF Nexus approach and technology in the African context, with a focus on Benin, was conducted. This included an exploration of previous studies, reports, and policy documents to establish a foundation for the research. General and Benin-specific knowledge was gathered on key themes like the WEF nexus, climate change, climate policies, NDCs, NAPs, and adaptation through documents including Benin's NDCs and NAPs, IPCC AR6, UNFCCC Convention, PANA Benin reports, and relevant scientific articles cited. Databases searched included Web of Science, Scopus, PubMed, Research4Life and ResearchGate. This informed understanding of WEF nexus status and policy integration in Benin. The WEF Nexus Index platform (Hoff, 2022) provided critical insights into characterizing sectoral linkages in Benin's national context.

Exploring the WEF Nexus index site (https://wefnexusindex.org/) has provided us with ample information on the state of the WEF Nexus in Africa and specifically in the Republic of Benin. This in-depth review enabled us to analyze the context of the Nexus WEF in Benin and the region.

4.2.2. Methodology to assess existing gaps in the integration of Nexus WEF technologies in Benin's climate policy documents

To effectively conduct this gap analysis, we first carried out a bibliometric analysis and then evaluated climate policy documents in Benin.

4.2.2.1. Bibliometric Analysis on Water, Energy, Food Nexus

Bibliometric analysis is a widely used tool that uses mathematical and statistical methods to assess research trends and growth (Li *et al*., 2020). For this research, a global bibliometric analysis was conducted using four databases (Web Of Science, Scopus, PubMed, Research4life). The following search terms were used: "Water-Energy-Food Nexus" and "World". The results were imported into the Biblioshiny management software to analyze publication trends, key authors, and the most cited journals. This method allowed us to map the scientific landscape of works related to the intersection of WEF Nexus technologies and climate policies. This method, employed by Alexander *et al*. (2023), is of undeniable relevance.

4.2.2.2 Assessment of the integration of the WEF Nexus into Benin's NDC and NAP

The matrix developed by the EU under the SWITCH-Med program was used to assess the level of integration of Nexus approaches in Benin's climate policies (NDC and NAP). This tool (table 1) takes the form of an evaluation grid containing 10 criteria systematically covering the three dimensions of the Nexus (water, energy, food) as well as their interactions. For each criterion, a grade from A to D was assigned after a thorough examination of Benin's Nationally Determined Contribution (NDC) and National Adaptation Plan (NAP). The matrix developed in the framework of the SWITCH-Med programme (EU, 2017) contains 10 criteria covering the three dimensions of the Nexus and their interactions. It uses a rating scale from A to D.

To apply this grid, we carefully reviewed Benin's climate documents (NDC, NAP) and assigned a score from A to D for each criterion. An overall score was then calculated, allowing the results to be graphically well presented.

Level A: Fully Systematically Integrated WEF Interactions for the Criterion

Level B: Some elements of integration but in a non-systematic way

Level C: Scattered mentions with little consideration of interactions

Level D: No reference to interactions for criterion

Table 1: SWITCH-Med Evaluation Grid

Criteria	**NDC**	**NAP**
Taking into account water-energy-food interactions		
Alignment of sectoral objectives		
Integration into national plans and strategies		
Institutional coordination		
The Influence of Dietary Goals on Energy Strategies		
Cross-sector data sharing		
Multi-stakeholder participatory governance		
Joint Risk Assessment		
Sustainable development of projects		
Regional cooperation		

This grid tool made it possible to quantitatively and qualitatively assess the integration of the Nexus into Benin's climate policy. This tool is recognized for its relevance and ability to quantify the level of Nexus integration.

4.2.2.3. Validation of the gap analysis and/or integration of the WEF nexus concept

In order to validate our research results conducted on climate planning documents in Benin, we held an interview and Focus Group Discussion with the Senior Consultant of the Government of Benin on the design of these documents, some Researchers, and Private Organization Actors. During this interview, our results were submitted to them for approval or not. Following this meeting, which was so strategic and enriching, it was a total approval of our results of studies of these climate planning documents in Benin, and they gave some strategies as the recommendations to fill the gaps identified.

4.2.3. Relative Methodology to the Specific and Adapted Recommendations to Fill the Identified Gaps in Benin's Climate Policies

To formulate specific and tailored recommendations aimed at filling the gaps identified in the consideration of Nexus approaches in the development of Beninese climate policies, extensive documentation was carried out. This included a detailed analysis of best practices and lessons learned from other countries and regions in integrating Nexus technologies. In particular, notable successes in North America, Europe and South Asia were the subject of extensive study. At the same time, a careful examination of Benin's specific socio-economic, environmental and institutional context was conducted. The specificities of Benin's water, energy and agriculture sectors were well understood, as were the challenges posed by climate change. The aim was to formulate recommendations that were fully adapted to national realities, with a view to maximizing the chances of their successful implementation.

The results of the evaluation of Benin's climate policies through the Nexus grids were then analyzed in depth. For each criterion that received a poor score, specific improvements were proposed. The latter combine both inspiration from international good practices and anchoring in the Beninese situation.

The final recommendations, set out in detail for decision-makers and key stakeholders, aim to promote truly integrated climate planning in Benin as in other countries in the region, with a view to sustainable development and strengthening resilience, as well as and above all the integrated and efficient management of resources in key sectors of activity.

5. RESULTS AND DISCUSSIONS

5.1. Analysis of the Interconnection and Interdependence of Water-Energy-Food (WEF) Sector Resources in Benin

5.1.1. Availability and accessibility of WEF sector resources in Benin

This graphical representation (Figure 9) clearly illustrates the evolution of the Water-Energy-Food Nexus Index (WEF Nexus Index) in Benin over the period 2019-2023. This index provides a quantitative measure of progress made in accounting for interdependencies across the water, energy and food sectors regarding key criteria of resource availability and accessibility. This provides useful insights into how the country has performed in accounting for interlinkages across water, energy and food sectors over this time period.

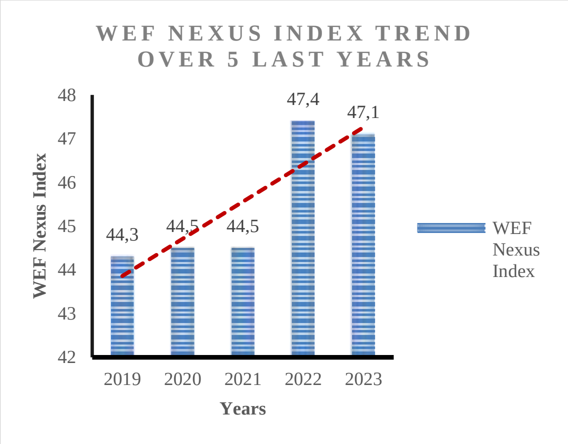
The figure 8 demonstrates a general upward trend in the overall WEF Nexus Index score, rising from 44.3 points in 2019 to 47.1 in 2023. This indicates steady progress has been made in integrated management of these key resource systems through Benin's implementation of a nexus approach.

When examining sectoral contributions, the data shows water consistently achieved the highest scores. In 2023 for instance, its rating was 52.9 compared to 35 for energy and 53.6 for food. This performance likely reflects Benin's emphasis on sustainable water governance reforms.

Energy followed in second place, with its rating growing from an initial 35.4 to close the period at 35 points. Expanding hydropower and renewable installations have likely supported these gains in energy accessibility and reliability over time.

Finally, food sector scores remained the lowest albeit reasonably stable near the 53 mark. This suggests more work is still needed to boost food security considerations within Benin's overall nexus framework.

At the sector level, access to water and energy increased, demonstrating meaningful steps toward achieving SDG 6 on clean water and sanitation and SDG 7 on affordable energy for all. However, declining water and energy availability is cause for concern, highlighting the need for robust measures to safeguard long-term supply security. The rise in food availability is a positive sign for food security efforts under SDG 2 on zero hunger. Nonetheless, availability is vulnerable to external factors such as weather and conflict.



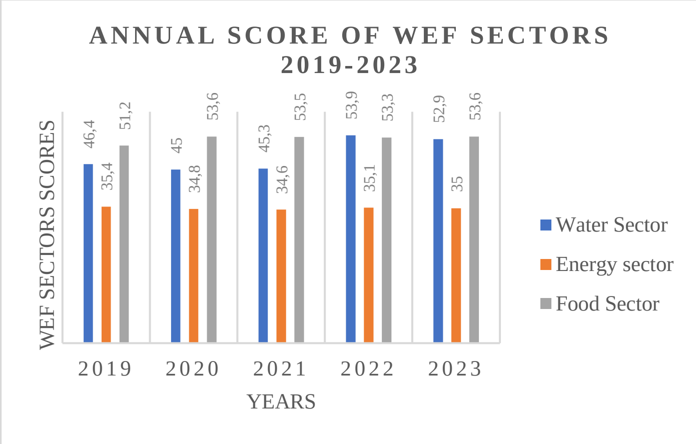


Figure 9: WEF Nexus Index Trend from 2019 to 2023

Figure 8: Yearly Score Contribution of WEF Sectors to WEF Nexus Index (2019-2023)

5.1.2. The interconnection and interdependence of WEF sector resources in Benin

The water, energy and food (WEF) sectors in Benin are highly interdependent in terms of both physical infrastructure and socio-economic activities. A WEF nexus approach that takes these interdependencies into account is important to ensure sustainable and resilient development in Benin's national context. An in-depth literature review enabled us to compile the following data:

Physical Interconnections

In Benin, irrigation plays a key role for the agriculture sector which represents 40% of GDP (FAO, 2021). According to the Ministry of Water (2022), 94,000 hectares of land are irrigated through water pumped from aquifers and waterways using energy-powered pumps. As noted by the FAO (2017), "irrigation depends on reliable water supplies and is also a major energy consumer" (p. 10). Additionally, the Nangbé and Djougou hydropower dams rely on flows from the Couffo and Ouémé rivers but these are subject to climate variability (Zan & Houssou, 2020). Per the SBEE (2021), during dry seasons, withdrawals for irrigation can reduce production from these dams by 20%. Thus, in Benin, the available quantities of water and energy directly condition agricultural and energy production.

Socio-Economic Interconnections

In Benin, the fisheries sector is strongly linked to water (Dewan *et al.*, 2019). It provides employment and nutrition to 600,000 people along coasts and waterways (FAO, 2018). However, pollution from agriculture and industry threatens these aquatic ecosystems (MAEP, 2019). According to SBEE (2021), discharges from settling basins at the Djougou palm oil mill caused fish deaths in the Ouémé River in 2012. Therefore, like irrigation, energy and agricultural activities have a direct impact on a vital sector for Benin's economy and nutrition.

Policy Interconnections

Benin's NAP and NDC have officially recognized the need to ensure integrated water and energy management in light of climate change (MECNT, 2021; MAEP, 2019). In this regard, the NAP recommends strengthening institutional capacities for harmonized planning of the water, energy and agriculture sectors. And in its NDC, Benin indicated its intent to further develop hydropower infrastructure to diversify its energy mix. These policies thus demonstrate growing acknowledgment by decision-makers of WEF system interrelationships in Benin.

The types of the WEF nexus approach resulting from the analysis of the interconnection of the WEF sectors in Benin

From the careful analysis of the results obtained above following an in-depth literature review, we can identify the types of WEF nexus technologies that are being implemented by the Beninese population unknowingly.

- **Water-Energy Nexus:**

1. Irrigation Technologies: The utilization of irrigation systems, including water pumping from aquifers and waterways using energy-powered pumps, exemplifies the interdependence between water and energy sectors. Energy is required for water pumping, and water availability directly influences agricultural production, highlighting the intricate connection between water and energy resources.

2. Hydropower Infrastructure: The operation of hydropower dams such as Nangbé and Djougou relies on the flow of rivers to generate electricity. However, their operation is subject to climate variability, indicating the dependence of energy production on water availability.

- **Water-Food Nexus:**

1. Irrigation Technologies: Irrigation plays a crucial role in supporting agricultural productivity, which constitutes a significant portion of Benin's GDP. The availability of water directly influences agricultural production, emphasizing the connection between water resources and food production.

2. Fisheries Management: While not explicitly mentioned, the fisheries sector's reliance on water resources for aquatic ecosystems underscores its association with the Water-Food Nexus. Technologies related to fisheries management, such as aquaculture techniques and sustainable fishing practices, likely play a role in supporting this sector.

- **Energy-Food Nexus:**

1. Fisheries Management: The fisheries sector, which provides nutrition and employment opportunities, may indirectly relate to the Energy-Food Nexus, as energy-intensive technologies may be employed in fisheries processing and distribution.

- **Water-Energy-Food Nexus:**

1. Policy Integration: Benin's national policies, particularly its National Adaptation Plan (NAP) and Nationally Determined Contribution (NDC), partially recognize the interconnectedness of water, energy, and food sectors. Strategies for integrated water and energy management in response to climate change demonstrate a holistic approach to addressing the Water-Energy-Food Nexus.

While Benin may not explicitly label its practices as part of the WEF Nexus approach, various technologies and policy measures indirectly contribute to the interconnected management of water, energy, and food resources. Recognizing and consciously integrating these practices within a coherent WEF Nexus framework could enhance their effectiveness and contribute to sustainable and resilient development in Benin

5.2. Assessing Existing Gaps in the Integration of the Nexus WEF Technologies in Benin's Climate Policy Documents

5.2.1. Bibliometric Analysis on Water, Energy, Food Nexus

Bibliometric analysis is an essential method in the field of scientific research, offering a comprehensive quantitative evaluation of scientific publications. It constitutes an indispensable tool for understanding the dynamics of scientific research, identifying emerging trends, existing gaps, and evaluating the impact of research in various fields of science, thus providing valuable insights for researchers, decision-makers, and stakeholders interested in advancing scientific knowledge.

Thus, to assess Benin's scientific production regarding the WEF Nexus issue to understand the gaps and Benin's contribution to this scientific dynamic, we conducted this bibliometric analysis on our research theme. The results obtained from this analysis allowed us to obtain precise and useful information.

Indeed, we observed that scientific production on the WEF Nexus worldwide from 2009 to March 2024 has experienced growth, with an increasing evolutionary dynamic in terms of the number of scientific publications and citations (Figure 10). Nowadays, we count more than 600 publications (including all types of documents) when considering databases such as Web Of Science, Scopus, PubMed, and Research4life. In the last three (03) years, the world has seen the largest number of scientific publications on the question of the WEF Nexus (Figure 10).

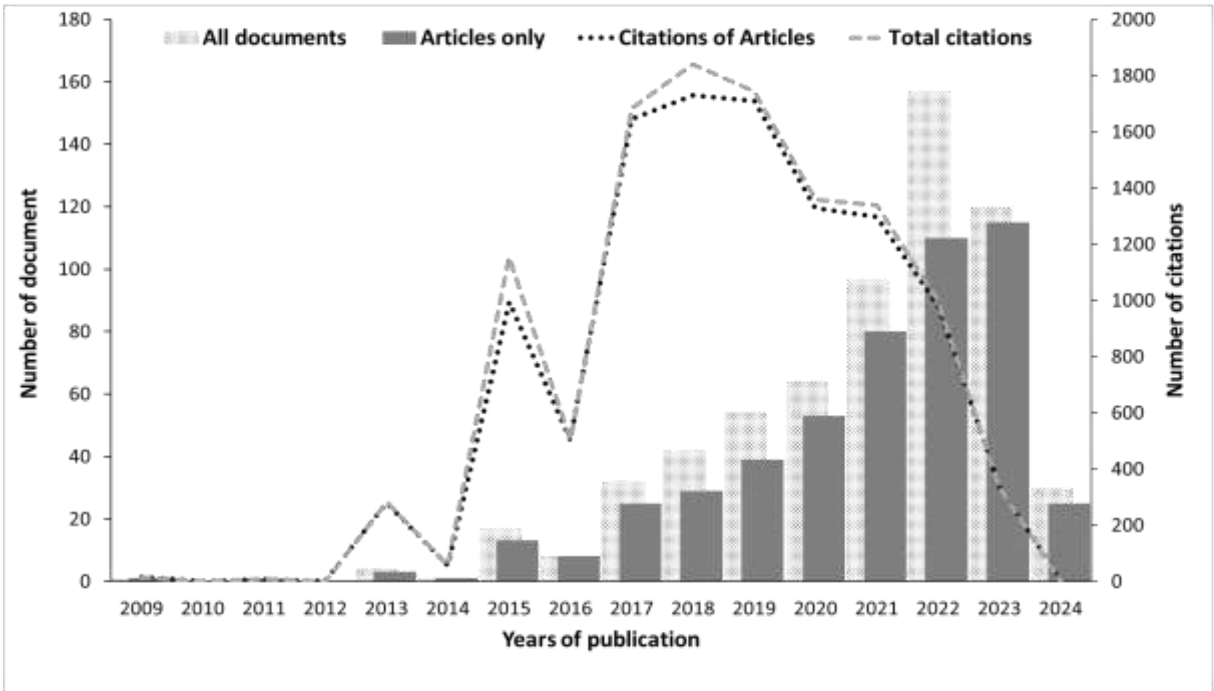


Figure 10: Evolution of scientific productions and total citation count from 2009 to 2024

The results from the table 2 show that the majority (over 97%) of the obtained documents are published in the English language. The publications obtained for the other six (06) languages are very minimal, totaling less than 3%. This includes Chinese (1.8%), French (0.2%), Persian (0.2%), Portuguese (0.2%), Ukrainian (0.2%), and Spanish (0.2%). This analysis highlights the importance of linguistic diversity in scientific research, emphasizing linguistic gaps. Thus, this observation prompts reflection on ways to promote greater linguistic diversity in scientific communication to enhance collaboration and inclusivity within the global scientific community.

Table 2 : : Number of scientific productions per language of publication and their percentage

Languages	**Number of publications**	**Percentage (%)**
Languages	Number of publications	Percentage
English	486	97.2
Chinese	9	1.8
French	1	0.2
Persian	1	0.2
Portuguese	1	0.2
Ukrainian	1	0.2
Spanish	1	0.2
Total	500	100.00

Furthermore, the figure 11 presents social networks of collaboration between countries regardless of the number of publications together. This graph allowed us to realize that while African countries, particularly Benin, exhibit a very weak network of collaboration with other countries worldwide, European countries (Germany, Spain, France, etc.), American countries (United Kingdom, United States, etc.), and Asian countries (China, etc.) show strong scientific collaboration on the issue of the WEF Nexus. Benin remains entirely undetectable in collaboration between countries having at least two publications (Figure 12), highlighting the shortcomings of Benin's low scientific contribution and collaboration on the WEF Nexus theme. This observation underscores the potential for improvement in Benin's international collaboration efforts in this crucial research area. Recognizing these shortcomings is essential for guiding research policies and initiatives aimed at strengthening Benin's participation in international scientific research on the WEF Nexus. Additionally, this finding emphasizes the importance of promoting transnational scientific collaboration to holistically address challenges related to water, energy, and food by facilitating the exchange of expertise, data, and best practices among countries. Finally, it also underscores the need to enhance research and collaboration capacities at the national level to ensure a more significant contribution from Benin to addressing WEF Nexus-related issues, thereby contributing to sustainable and equitable development globally.

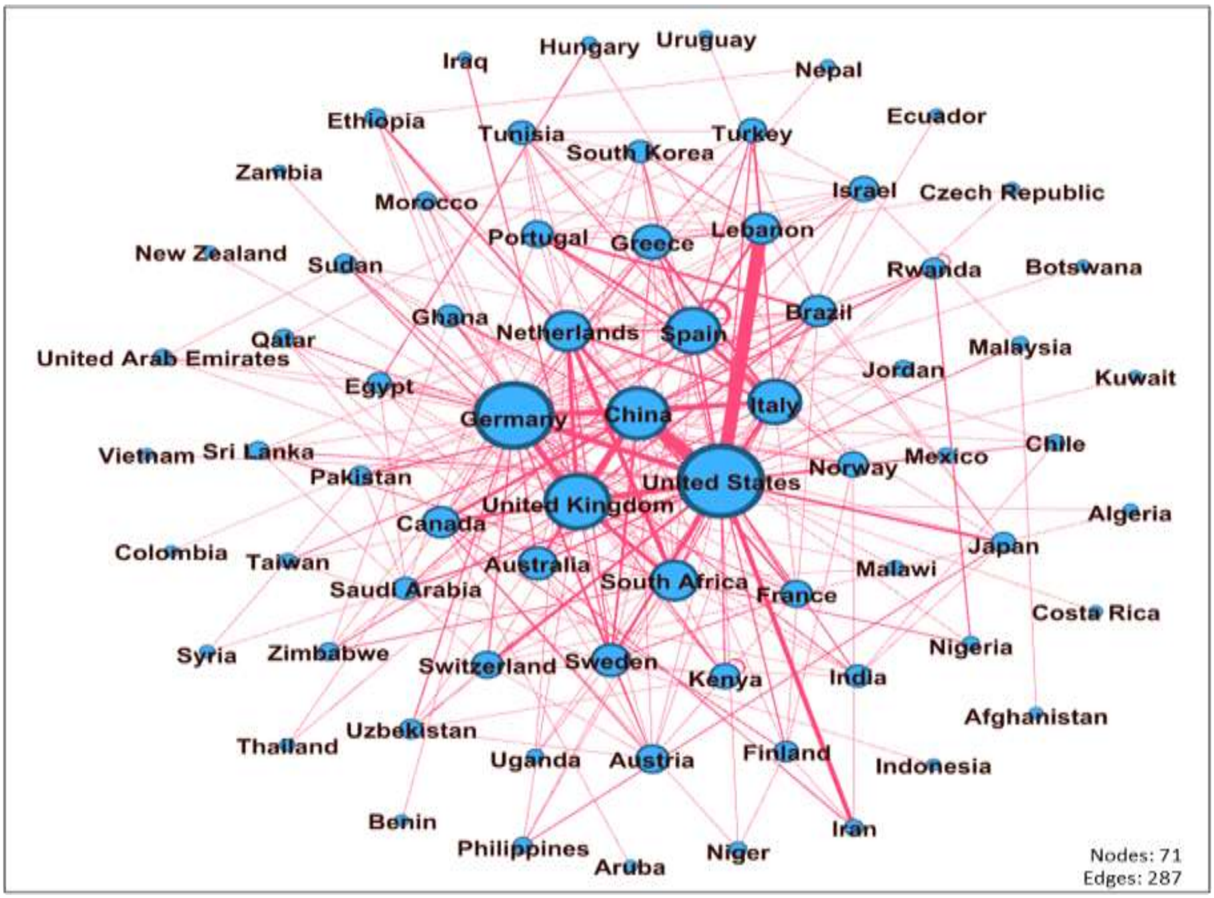


Figure 11: Social networks of collaboration between countries regardless of the number of publications together

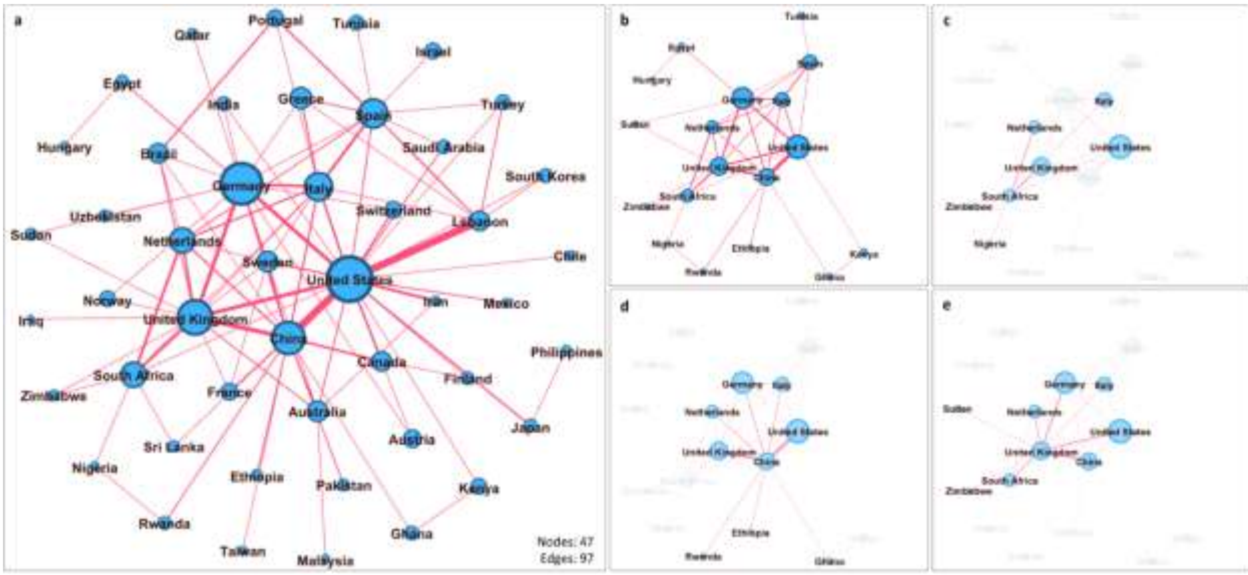


Figure 12: : Social networks of collaboration between countries having at least two publications together (a), with African countries nodes (b), with countries linked with South Africa (c), with countries that have collaborated with three African countries (d and e)

The map (Figure 13) showing the number of publications per country worldwide (Figure) confirms the previous results and highlights the contribution of each country to scientific publications. Analyzing this figure has enabled us to understand that no country in West Africa, including Benin, except Ghana, has published more than four (04) papers on the topic since 2009. Furthermore, no African country, except South Africa, has published more than nine (09) scientific documents. This demonstrates the shortcomings in the low scientific contribution of the African continent on the WEF Nexus theme. It indicates that this topic remains uncharted territory and underscores the urgent need to strengthen research capacities in this region, particularly in WEF Nexus, to bridge this gap and promote sustainable development. It thus highlights a critical need for investment in research and development in Africa, as well as the necessity to foster inclusive and collaborative partnerships to advance understanding and resolution of WEF Nexus-related issues globally.

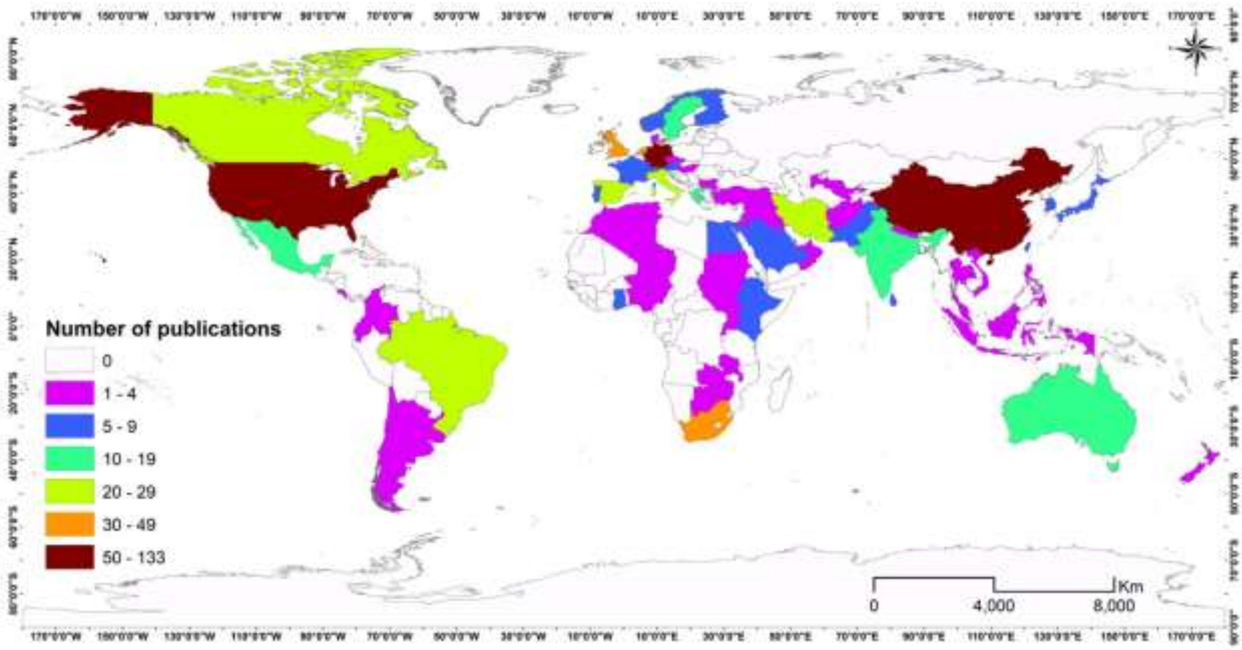


Figure 13: Map showing the number of publications per countries worldwide

The results of the bibliometric analysis (figures 8, 9, 10, 11, 12, 13, and table 2) reveal significant gaps in Africa's scientific contribution, particularly in the field of Water-Energy-Food (WEF) Nexus. It is striking to note that, except for South Africa, no African country has published a significant number of scientific documents on this subject. Additionally, for West Africa, including Benin, the contribution to research on the WEF Nexus is even more limited, with only a few publications in recent years.

This finding raises important concerns about the ability of African countries, especially those in West Africa, to fully participate in scientific discussions and research initiatives on crucial issues such as the WEF Nexus. These gaps can be attributed to various factors, including lack of funding for research, limited research infrastructure, lack of awareness and training of researchers in this specific domain, as well as national and regional research priorities.

For Benin specifically, these results underscore the urgent need to strengthen research and development capacities in the field of WEF Nexus. It is imperative that the government, academic institutions, and development partners commit to supporting and promoting scientific research in this crucial area. This will require increased investment in research infrastructure, enhancement of local researchers' skills, promotion of international collaboration, and establishment of strategic partnerships with research institutions and funding agencies.

5.2.2. Gaps Analysis of the Integration of WEF Nexus Technologies into National Climate Policies

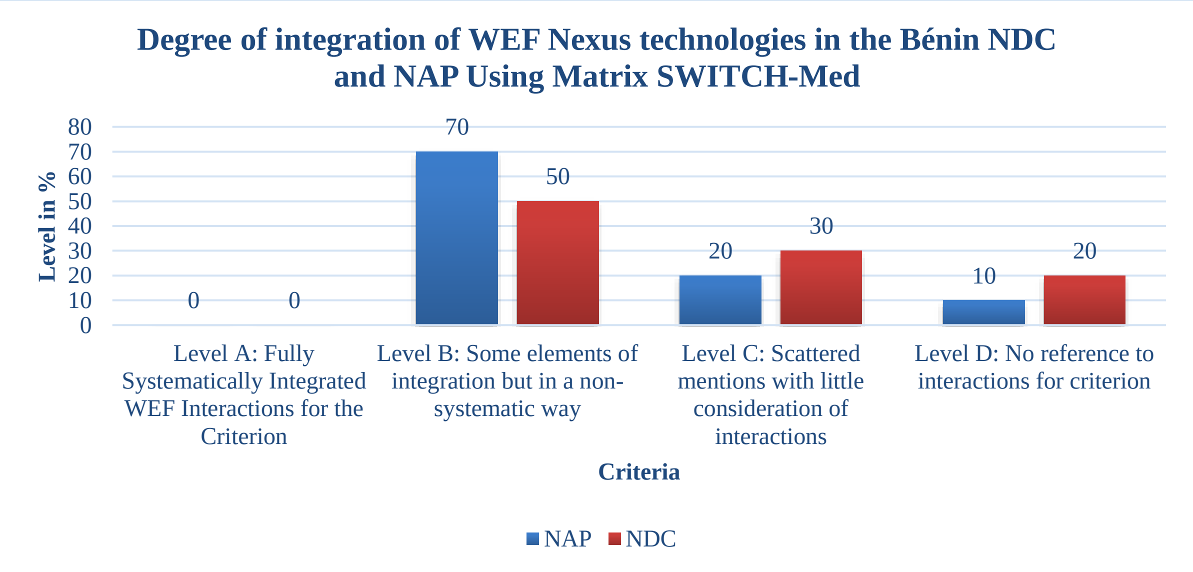


Figure 14: Degree of integration of WEF Nexus technologies in the Benin NDC and NAP Using Matrix SWITCH-Med

Analysis of the degree of integration of water-energy-food nexus technologies into Benin's climate policy documents (NDC and NAP) (Figure 14) reveals a limited incorporation of this systemic approach, suggesting potential difficulties in the planning and coherent implementation of concerted actions on these interconnected sectors.

Utilizing the matrix developed by the EU under the SWITCH-Med program to evaluate this integration level, the graph (figure 14) provides a comprehensive overview of the extent to which WEF Nexus technologies are incorporated into Benin's climate documents. The values presented in the graph reflect the assessment of different levels of integration, ranging from Level A, indicating full systematic integration of WEF interactions, to Level D, signifying no reference to interactions for the criterion.

Upon analyzing the graph, it is evident that there is room for improvement in the integration of WEF Nexus technologies in both NAPs and NDCs in Benin. From this graph, we can remark the followings:

- Level A (Fully Systematically Integrated WEF Interactions for the Criterion): The absence of any documents rated at Level A suggests that Benin's climate documents do not comprehensively and systematically integrate WEF Nexus interactions. This indicates a significant gap in the consideration of interconnections between water, energy, and food sectors in the country's climate policies.

- Level B (Some elements of integration but in a non-systematic way): The graph shows that 70% of NAPs and 50% of NDCs are rated at Level B. While there are some elements of integration present in these documents, they are not systematically integrated. This suggests that while there may be some acknowledgment of WEF Nexus interactions, they are not fully integrated into the overall framework of the climate documents.

- Level C (Scattered mentions with little consideration of interactions): Approximately 20% of NAPs and 30% of NDCs fall under Level C. This indicates that these documents contain scattered mentions of WEF Nexus interactions but provide little consideration for their significance. There is a need for more explicit recognition and consideration of these interconnections in future revisions of the documents.

- Level D (No reference to interactions for criterion): The lowest level of integration is observed in 10% of NAPs and 20% of NDCs, where there is no reference to WEF Nexus interactions for the criterion. This signifies a lack of acknowledgment of the interdependencies between water, energy, and food sectors in these documents.

These findings, supported by quantified indicators, demonstrate a lack of coordinated approach between the water, energy and food sectors in the country's strategic plans.

The analysis of the graph underscores the importance of enhancing the integration of WEF Nexus technologies in Benin's NAPs and NDCs. Addressing these gaps is crucial for ensuring holistic and sustainable climate policies that effectively manage water, energy, and food resources in the face of climate change. It is imperative for decision-makers and stakeholders to prioritize the incorporation of WEF Nexus considerations into future revisions of climate documents to promote resilient and adaptive development pathways in Benin.

- ✓ **Gap Analysis in the Integration of WEF Nexus Technologies into Benin's NDC: Remarks**

- Benin's NDC sets ambitious targets for the key sectors of agriculture, water and energy, but there is a lack of explicit coordination between these sectors for a holistic approach to the WEF Nexus.

- Although specific strategies for the agriculture and water sector are mentioned, such as rehabilitating irrigation infrastructure and improving water resources management, there is little indication of promoting sustainable practices that integrate energy.

- Measures to improve energy efficiency in agriculture, such as the adoption of solar technologies for irrigation or the use of biofuels for agricultural activities, could be strengthened for a more integrated approach to the WEF Nexus.

- Water governance in Benin's NDC appears to be a strong point, with strategies for integrated water resources management, including the rehabilitation of water infrastructure and the promotion of participatory water resources management.

- However, there is a lack of details on the adoption of innovative technologies for sustainable water management, such as the use of smart sensors for water quality monitoring or the application of precision irrigation techniques for efficient water use.

- Stakeholder involvement in decision-making related to water management could be strengthened by establishing public consultation mechanisms and promoting the participation of local communities in the planning of water-related projects.

- ✓ **Gap Analysis in the Integration of WEF Nexus Technologies into Benin's National Adaptation Plan (NAP): Remarks**

After a detailed review of the content of Benin's National Adaptation Plan (NAP), it appears that the document addresses water, energy and food aspects, but there is a need for further analysis of how the technologies of the WEF Nexus are integrated.

The integration of WEF Nexus technologies into Benin's NAP reveals significant gaps that require attention to strengthen the sustainability and resilience of the water, energy and food sectors to climate change. The evaluation based on "SWITCH-Med programme" evaluation Grid highlights the following points:

- Integrated Water, Energy and Food Management

Although the NAP addresses these three sectors separately, there is a lack of a holistic approach that fully integrates the interactions between water, energy and food in the operationalization of activities in these three different sectors. The potential synergies between these sectors are not fully exploited to promote integrated resource management.

- Specificity of WEF Nexus Technologies

The specific technologies of the WEF Nexus are not clearly identified in the NAP. There is no mention of any technology deemed qualified by the WEF Nexus in Benin's NAP. This reflects the lack of knowledge of these technologies, which promise a more integrated and efficient management of the various resources of these three interconnected sectors of activity. It is essential to define innovative technological solutions that promote efficient use of water and energy resources while ensuring food security, thus aligning actions with the principles of the WEF Nexus.

- Concrete Actions for Implementation

The NAP lacks details on concrete actions and atypical procedures to be undertaken to integrate WEF Nexus technologies. Despite the performance of these three sectors in the WEF Nexus Index, the lack of concrete action remains alarming regarding the adoption of WEF Nexus technologies in the design and implementation of the NAP.

5.3. Specific and Adapted Recommendations to Fill the Identified Gaps in Benin's Climate Policies

The implementation of the WEF nexus technologies integration process into local development planning requires initial efforts to ensure the strengthening of institutional and trans-sectoral links between the various structures involved in the implementation of activities and the active participation of stakeholders from key sectors. Institutional links are needed between the entities responsible for conducting the targeted planning document process (Nationally Determined Contribution and National Adaptation Plan); the competent services of decentralized services responsible for planning and development (local planning and development service); and environmental issues (Benin Environmental Agency). It is crucial for these links to strengthen over time to ensure the sustainability of the actions taken. In addition to these institutional links, active participation from local communities is crucial in the process. The integration process will be led by a multi-stakeholder and multidisciplinary commission established with all stakeholders. Indeed, after thorough interviews with some key actors (seasoned researchers and ministerial actors), the following recommendations are to be considered:

5.3.1. Integration at the level of the NDC and NAP document elaboration process

- Strengthening of intersectoral coordination from the inception phase of national climate policies to ensure a holistic and integrated approach.
- Explicit identification of specific WEF nexus technologies in the NDC and NAP documents to promote effective and sustainable management of water, energy, and food resources.
- Promotion of sustainable practices integrating energy, such as the adoption of solar technologies for irrigation and the use of biofuels for agricultural activities, for a more integrated WEF nexus approach.

5.3.2. Integration at the level of sectoral and decentralized implementation processes

- Training and awareness-raising of actors involved in the implementation of national climate policies to enhance capacities in WEF nexus integration.
- Establishment of monitoring and evaluation mechanisms to measure the impact of integrating WEF nexus technologies in key sectors such as agriculture, water, and energy.
- Strengthening of multi-stakeholder collaboration to ensure effective and efficient implementation of recommendations, by fostering coordination among stakeholders from different sectors.

5.3.3. Methodological framework for the implementation of recommendations

1. Development of specific guidelines for WEF nexus integration:

Development of clear guidelines for integrating WEF nexus technologies into national climate policies, defining specific criteria for the identification and adoption of these technologies.

2. Training and awareness-raising of actors involved in implementation:

Implementation of training and awareness programs to enhance the capacities of actors involved in the implementation of national climate policies, focusing on the importance of the WEF nexus approach and associated technologies.

3. Monitoring and evaluation of the impact of WEF nexus integration:

Establishment of a monitoring and evaluation system to measure the impact of integrating WEF nexus technologies in key sectors, allowing for adjustments of strategies and actions based on the results obtained.

4. Strengthening of multi-stakeholder collaboration: Promotion of strategic partnerships between governmental actors, academic institutions, civil society organizations, and the private sector to ensure effective and efficient implementation of recommendations.

By following these recommendations and implementing a robust methodological framework, Benin can strengthen the integration of WEF nexus technologies into its national climate policies, thus promoting a more resilient and sustainable approach to the management of water, energy, and food resources.

6. CONCLUSION AND RECOMMENDATIONS

The present study focuses on the integration of Water-Energy-Food (WEF) Nexus technologies into the development and implementation of national climate policies in Benin, West Africa. The objective was to propose strategies to promote the integration of WEF Nexus technologies into the design and implementation of Benin's Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs). It is essential to note that the results reveal significant availability of resources in the three different sectors of the WEF Nexus, but accessibility remains to be strengthened, leaving Benin with a significant increase in its WEF Nexus index over the past five years (from 44.3 points in 2019 to 47.1 in 2023). The results also identified significant gaps in the integration of WEF Nexus technologies into Benin's climate policies, including limited sectoral management of available resources, lack of coordination and trans-sectoral integrated management, as well as low scientific production on the theme of the WEF Nexus in Africa, particularly in Benin. Benin already practices some types of WEF Nexus technologies, including bi-sectoral ones (Water-Energy Nexus, Water-Food Nexus, etc.). Although Benin's NDCs and NAPs do not explicitly mention WEF Nexus technologies, they partially and indirectly address them. This allowed, after evaluation, to observe a significant level of partial integration in both documents (70% in the NAP and 50% in the NDC). These results for policies and practice emphasize the need to promote truly integrated climate planning in Benin, focusing on optimized resource use, multi-benefit projects, and trans-sectoral coordination to strengthen climate action and sustainable development. Furthermore, specific recommendations have been formulated to address the identified gaps, with the aim of enhancing Benin's participation in international scientific research on the theme of the WEF Nexus. Finally, limitations have been identified, including the need to conduct future research on the environmental aspect of the nexus (Water-Energy-Food-Environment Nexus) for better resource management while respecting the environment.

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ANNEXE

Table 3 : "SWITCH-Med programme" Evaluation Grid

Criteria	**NDC**	**NAP**
Taking into account water-energy-food interactions	B	B
Alignment of sectoral objectives	D	D
Integration into national plans and strategies	B	B
Institutional coordination	B	B
The Influence of Dietary Goals on Energy Strategies	C	C
Cross-sector data sharing	C	B
Multi-stakeholder participatory governance	C	C
Joint Risk Assessment	D	B
Sustainable development of projects	B	B
Regional cooperation	B	B

Legend :

Level A: Fully Systematically Integrated WEF Interactions for the Criterion

Level B: Some elements of integration but in a non-systematic way

Level C: Scattered mentions with little consideration of interactions

Level D: No reference to interactions for criterion

Fiche-questionnaire d'entretien

Enquêté N° :	Lieu et Heure de l'entretien :	
Nom complet (Facultatif) :		Secteur :
Sexe :	Institution :	Profession :

Titre de l'étude : Analyse des lacunes dans l'intégration des technologies du nexus Eau-Énergie-Alimentation (WEF) dans la conception et la mise en œuvre des politiques climatiques nationales du Bénin (NDC et NAP)

Objectif de l'entretien : Validation des résultats de recherches et obtenir des recommandations des experts et des agents ministériels pour combler les lacunes identifiées.

L'objectif spécifique 1 : Evaluer l'interconnexion des ressources des secteurs du nexus WEF

Résultats obtenus : Ressources disponibles mais leur accessibilité limitée. Les ressources disponibles des 3 secteurs sont beaucoup plus gérées de manière sectorielle, ce qui laisse constater une gestion trans-sectorielle passable. La population n'a aucune idée des opportunités qu'offre la gestion intégrée (trans-sectorielle) des ressources de ces secteurs.

Avis de l'interviewe :

L'objectif spécifique 2 : Analyse Gaps de l'intégration des technologies du nexus WEF dans NDC et NAP

Résultats obtenus : l'analyse bibliométrique révèle des lacunes latentes du Bénin en matière de réseautage et de recherches scientifiques en matière du Nexus WEF.

Manque d'informations sur le sujet dans le NDC et NAP. 70% d'intégration (E-E, E-A) dans le NAP et 50% dans le NDC. Absence totale de coordination et de gestion intégrée trans-sectorielle de tous les secteurs du WEF ensemble.

Avis de l'interviewe :

L'objectif spécifique 3 : Proposer des stratégies adéquates pour favoriser l'intégration des technologies du nexus WEF dans la conception et la mise en œuvre des NDC et NAP

Résultats : seront issus des entretiens

Avis de l'interviewe: A la lumière des résultats obtenus, quelles sont les recommandations ou stratégies que vous proposez pour combler ces lacunes identifiées, et favoriser la reconnaissance et l'intégration des technologies du nexus WEF dans la conception et la mise en œuvre des NDC et NAP?